GEORGE HUNTER.

Summary

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The apparatus in which the suspended clouds were sprayed is described. It consisted of a cylindrical dust chamber of large volume into which the dust was injected and dispersed.

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The following conclusions were drawn from the work.

It was found that the spray variables could be connected by an empirical formula by which droplet size could be predicted at any pressure, provided two relevant points were determined experimentally. A relationship was also obtained between the energy applied to the spray and the energy used in the atomisation process.

In general, atomisation was found to increase with increase in spray pressure and cone angle and decrease with increase in orifice diameter and with the distance from the spray nozzle.

The efficiency of atomisation was found to be much lower than expected, indicating that a high proportion of the energy imparted to the spray was not utilised in the atomisation process.

The use of solutions of low surface tension was found to have little effect on the atomisation achieved. Only below 30 lb./in^2 was any improvement obtained. The two methods of droplet sampling employed were found to give reproducible and comparable results if sufficient samples were taken.

It was thought that the energy required to effect equivalent atomisation of the solutions of low surface tension would be less than that required for water. This was not so and it

is concluded that at the moment of droplet formation the surface tension is not the equilibrium value but some dynamic value, possibly higher than the equilibrium value.

Change of surface-active agent concentration was only found to affect atomisation at low pressure owing to the effect on the surface tension of the solution. At higher pressures concentration of surface-active agent would only affect atomisation through viscosity or density increases. Spraying tests showed that the dust clouds (coal dust, silica dust and fly ash) were affected by aqueous sprays and that the amount of dust removed was in each case increased when

(a) the duration of spraying was increased

(b) the average droplet size was increased over the range investigated (33 - 96 microns)

(c) the relative velocity of the droplets was increased

(d) cyclohexane was used at low spray pressures.

Estimation of the size distributions of the dust clouds under different conditions led to the following conclusions :

(a) the size distribution of the clouds alters very slowly with time after the first 90 minutes

(b) the small particles aggregate to follow large particles

(c) the large aggregates settle out

(d) spraying removes the larger particles and breaks up the aggregates

(e) cyclohexane appears to remove more of the dangerous size fraction than the other liquids tried.

It would appear that the most effective droplet size is greater than 96 microns for the clouds sprayed.

A dust sampler was developed capable of collecting a representative sample of the dust in suspension (coal dust or silica dust) and is described.

It is capable of collecting, in a reasonable time, a sample sufficiently large to allow chemical analysis to be carried out. Only 100 mgm. of the total weight of dust collected (ca 5 gm.) is retained in the pores of the collecting thimble. It has also been shown to compare favourably with another bulk sampler now being produced commercially.

PHYSICO-CHEMICAL STUDIES ON DUSTS :

THE EFFECT OF AQUEOUS SPRAYS ON AIRBORNE DUSTS

BY

GEORGE HUNTER, B.Sc., A.R.C.S.T., A.R.I.C.

A thesis submitted to the University of Glasgow
in fulfilment of the requirements
for the degree
of Ph.D. in Science.

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INTRODUCTION.

Pneumoconiosis.

Pneumoconiosis is the general term given to diseases of the lungs, fibrous and non fibrous. It was first used by Zenker (1) in 1867 and signified a lung full of dust. Silicosis and asbestosis are the most important forms of pneumoconiosis. Names such as siderosis, anthracosis, anthracosilicosis, siderosis and byssinosis have been given to other forms of pneumoconiosis.

The severity of the problem is indicated by the fact that 4848 cases (2) of pneumoconiosis were certified in British pits in 1956. For the past eight years only once has the number of certifications fallen below 3500. In 1955 (3) between 20 and 40 deaths due to asbestosis and byssinosis were recorded and the total number of deaths in all types of industry in Britain, from 1953 to 1955, due to silicosis was in the region of 1700 per annum. The additional deaths due to asbestosis, pneumoconiosis, byssinosis and other types of fibrosis brought the total to ca 2000 per annum.

History of Silicosis.

Silicosis is not a new disease although its incidence has undoubtedly been increased by the modernisation of working methods; indeed, the first reference to industrial disease due to dust was made in the pre-Christian era when Hippocrates noted symptoms in metal-diggers similar to those described in

more modern accounts of pneumoconiosis. The importance of excluding dust from the air was recognized in the first century A.D. by Pliny (5), who described a protective mask for miners. In the Middle Ages the subject was referred to by Agricola (6) and Paracelsus (7), the former recommending the use of respirators. Paget (8) in 1834 was the first writer to discuss miners' lung disease in detail and in 1869 Von Zimmerbrock (9) made what was probably the first section of a stone-cutter's lung, revealing the way in which it was clogged with dust.

The fact that not all dust was injurious was recognized by Knaggs (10) in 1832. His study of the expectation of life in various dusty trades had shown that hardly any lung disease occurred among brick and limestone workers, whereas workers in sandstone quarries were plagued by dust disease. In 1831, Gregory (11) reported " a case of peculiar black infiltration of the whole lungs resembling melanosis" The difference between exposure to coal dust and exposure to a dust containing large amounts of free silica was not, however, realized.

Pancoast (12) and Greenlaw (13) recognized the presence of hard, gritty particles in lung sections, and Pancoast drew a distinction between dust phthisis and pulmonary tuberculosis. Physicochemical evidence obtained by Greenlaw using polarized light showed that the lungs of metal grinders contained a proportion of fine silica particles.

The relationship between the inhalation of siliceous dust and the development of certain pathological changes in the lung was first designated silicosis by Visconte (14). Thus, the idea of noxious dust was finally connected with silica.

Mechanism and Causes of Dust Diseases.

Dust diseases are caused primarily by the inhalation of airborne dust. The particles of dust inhaled may be up to 100 microns in diameter.

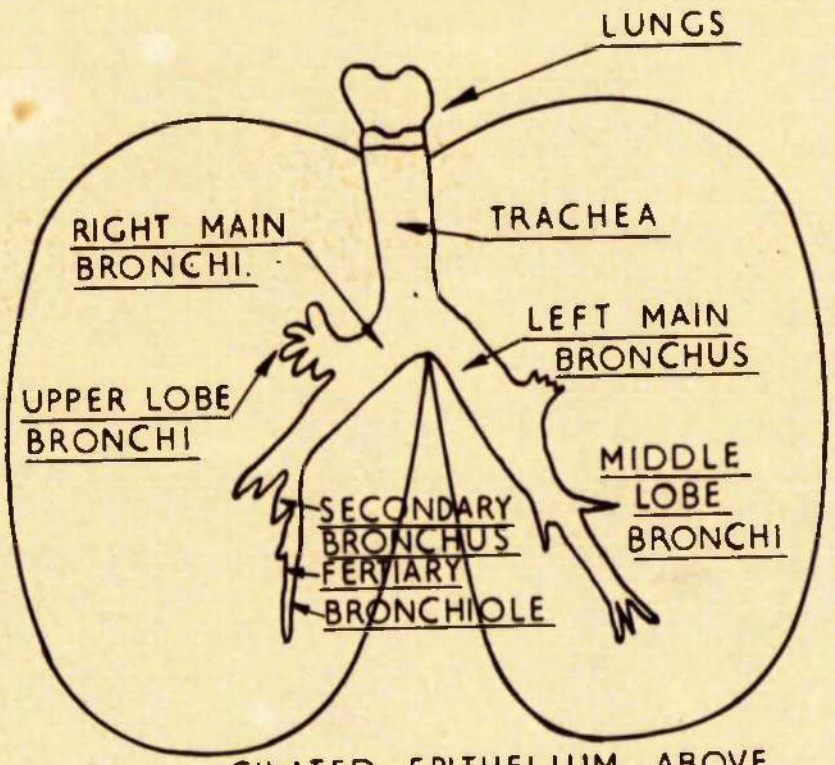
The lung is protected from the accumulation of foreign particles by certain mechanisms. The nose through which the respiratory tract opens to the surface of the body is guarded by a coarse filter of hairs in which some dust is trapped. There are also tortuous moist passages to the walls of which dust particles can adhere.

This defence mechanism is, however, easily overloaded and is functions less efficiently the smaller the dust particles become. The inefficiency of the nose in retaining dust of small particle size has been established by Lavies (15), Landahl and Black (16), and Boyland et al. (17). A filtering device which will retain respirable dust will impose a considerable resistance to breathing.

Thus a dust particle of about 25 microns is likely to be caught in the nasal passages or at the back of the throat. It may pass into the bronchi (Fig.1.) but it is extremely unlikely that it will reach the alveoli. The collection of

FIGURE 1

THE BRONCHI.



particles depends on their impaction against the moist walls of the respiratory tubes which will be more effective the larger the particle. Lining the trachea and extending down to the lower ends of the bronchioles are myriads of cells with whiplike appendages, called cilia, which carry upwards any foreign bodies that chance to touch the wet mucus-bathed linings of the respiratory passages. The upward movement of the mucus is maintained, by the lashing of the cilia, at the rate of three or four centimetres a minute in the trachea. Heavy experimental injections of dust in animals are cleared in a matter of hours. Most of the inhaled dust deposits on the mucous lining, and unless the particles are soluble or have mechanical action they are excreted without doing any harm. If the action of the cilia is in any way impaired the deep lung may be exposed to infection.

If particles succeed in passing these barriers and penetrating the terminal air spaces of the lungs they are ingested by wandering scavenger cells or phagocytes, which come from the partitions between the air spaces. These cells move independently and tend to carry the foreign bodies out of the air spaces into a special drainage system known as the lymphatics. The protective mechanisms mentioned are normally adequate but are unable to cope

in a dusty atmosphere is breathed for long periods. The membranes are damaged and dust particles collect where air should be (10).

All dusts are not phagocytosed at the same rate. Easton (17) maintained that coal dust is phagocytosed more quickly and more completely than stone dust and Fenn (20) found that quartz was damaged more least easily phagocytosed by the cells.

The play of dust finally to be harmful is still the subject of a great deal of speculation. Different authorities have found, in the lungs of diseased miners, dust ranging from 0.2 micron to as large as 10 microns(21,22,23). Recently an electron microscope study of dust from miners' lungs has shown practically no coal dust above 2 microns(24). However, it is thought that the harmful size range is 0.2 micron - 5 microns. Nagelschmidt (25) has recently indicated a relationship between the amount of dust deposited in the lungs during inhalation (during work) and the amount in the air. This relationship is considered by the behaviour of particulate matter in the respiratory system. It has long been known that only a fraction of the inhaled dust is retained and that the percentage retention varies with particle size.

The exact process by which fibrous tissue is formed in the lung because of the presence of dust is not known, but does appear to involve only particles that penetrate to the alveoli and remain for a considerable period. The accumulation of inert dust in the lung may prove harmful and interfere with respiration. Other dusts of low solubility may also remain in the lung and promote the growth of fibrous tissue. Silica is highly unsoluble, and interferes seriously with respiration leading perhaps to disease.

Dust in Coal Mines.

The dust produced in mining varies greatly with the strata, type of coal, height of the coal bed, mining methods, and the degree of ventilation. The various dust-making processes may be described under the headings : mining, blasting, cutting, conveying, loading and preparation. Modern methods of production have materially increased the dust hazards in mining.

In still air, dust settles out under gravity at the rates shown in Table I below.

Particle Diameter Microns	Terminal Velocity cm./sec.
0.2	0.000025
1	0.003
5	0.076
20	0.30

Unfortunately, the most dangerous dust settles least quickly, and, as ventilation is necessary, it mostly remains airborne and available for inhalation for a considerable time. The velocity of air along working faces is of the order of 100 ft./min. and varies greatly along the roadways. It is found, however, that the airborne concentration of 5 micron dust only drops about 5 per cent in 500 yds of roadway. A proportion of $\angle 5$ micron dust is therefore sometimes found in the exit air shaft. The harmful dust concentration does decrease with distance from the working face and by the time the coal has reached the preparation plant it is very low.

Drilling and shotfiring usually produce finer dust, with a higher silica content, than cutting, conveying and loading. Dust concentrations vary a great deal. At a coal face the concentration and composition of the dust obtained vary every few feet of advance. Concentrations obtained at the working face may be anything from 45 to about 5,000 particles per cc. of 0.2 - 5 micron size but more often the figure is in the regions of 400 particles per cc. The National Coal Board, as the result of measurements carried out over long periods, have suggested suitable limiting dust concentrations. These are for coal dust

(anthracite only) 650 particles per cc. of size 1 - 5 microns ; all other coal dusts 850 particles per cc. of size 1 - 5 microns ; and rock dusts 450 particles per cc. of size 0.5 - 5 microns.

An appreciable contribution to atmospheric dust comes from the disturbance of loose-surfaced haulage and travelling roads. Some of the smaller dust may be carried down as aggregates. If unconsolidated this might be disturbed, along with other loose dust, and become airborne once more. High concentrations of fine dust are liable to be explosive. It is therefore advisable to consolidate such dust. This has been done successfully with calcium chloride solution and has been found to be effective for about 6 months (26,27,28).

Dust Sampling

To estimate the health hazard of an airborne dust, a representative sample of it has to be taken. This requires a suitable sampling instrument to extract the dust particles from the atmosphere and concentrate them in such a way as to allow subsequent measurement of the number and size of the particles, or of the weight of collected dust. An important point in the evaluation of health risk is that the collected dust particles should be exactly as they were in suspension. Available sampling instruments may be classified according to the physical basis of operation as follows :

(a) [illegible]

(b) [illegible]

(c) [illegible]

(d) [illegible]

(e) [illegible]

[illegible] to be given depends on whether a gene probe for multiple or one for cloning and assay is required.

[illegible] provides a fundamental means of obtaining the absolute concentration of particles larger than about 0.2 micron. Applied continuously over a stable volume of air will give the total mass concentration in a large volume. Because of its low sampling rate of many cubic centimetres, however, the time required to collect a sample is long, and, as a result, this method is not suitable for routine sampling.

Dust can be sampled from gases by filtration, but this necessitates drawing a large volume of the dusty gas either by means of a vacuum pump, and aspirator, or a motor, through a weighed filter paper or cotton wool plug. The concentration of this dust in the original gas is found by re-weighing.

One instrument utilising the filtration principle is the P.R.U. Hand Pump (29), which enables an estimate of the dust concentration to be made by comparison of the dust stains obtained on pieces of filter paper.

Several dust samplers employ the principle of impingement. Instruments of this type are :

(a) Kotze Konimeter (30)

(b) Owens Jet Dust Counter (31)

(c) Bausch and Lomb Counter

(d) Cascade Impactor (32)

(e) Standard (33) and Midget Impinger (34)

In these instruments dust laden air drawn by suction is allowed to impinge at high velocity perpendicularly against a collecting surface. The sudden change of direction of the air-flow, combined with the inertia of the particles, results in the separation of the dust from the air on the collecting surface. However, these instruments are found to have low collecting efficiencies for particles less than 2 microns in diameter. They also tend to break up larger particles or aggregates, either in the jet or on the plate, producing particles smaller than those present in the original dust cloud. The sample taken must not be too large, or the collected particles will overlap, so that it is

impossible to assess them microscopically. These instruments therefore do not give a truly representative sample.

Electrostatic precipitation has been used to collect small samples of dust; but it has not yet been modified for use in coal pits.

Green and Watson (35), in 1935, utilised the principle of the dust - free area which is found around a hot rod to provide a suitable dust sampling instrument. This instrument called the Thermal Precipitator gives a direct deposition of dust particles from the aspirated air on to a glass cover slip which can then be mounted on a microscope slide and examined. Comparison of the collection efficiency of the instrument with results obtained using the absolute sedimentation cell show that within the limits of experimental error and of optical microscopy the efficiency is of the order of 99 per cent with particle diameters of less than 5 microns. The instrument is less reliable when the dust particles are greater than 10 microns. Owing to its high efficiency in the region of greatest importance, however, it is now used in preference to the impinger type of apparatus to evaluate dust samples for routine analysis and research work.

Dust Suppression

The elimination of dust can be accomplished in two ways :

(a) By the prevention of dust formation at the source.

(b) By the subsequent removal of the airborne dust.

Ideally, if the production of dust is inevitable, it should be suppressed at the source. Once it becomes airborne and is diluted with clean air it becomes more difficult to remove.

Water has been used for dust suppression in mines (36, 37) and is generally applied in the form of a spray. This property of water was recognised by Thomas Benson of Newcastle-under-Lyme, who, in 1726, obtained patents for the wet grinding of flint.

Two types of spray have been used in mine dust suppression, the swirl atomiser type and the compressed-air-operated spray. According to the literature, while it is well established that wetting the coal or rock before and during cutting greatly reduces the dust subsequently dispersed to the atmosphere (38,39), the evidence regarding removal of airborne dust by spraying and other means is not so conclusive.

Coagulation of small particles by acoustic vibrations is possible, but has not yet been applied in mines (40). Electrostatic precipitation, although effective, carries many difficulties which have to be overcome before it could be used as a means of suppressions in mines.

Sprays at transfer and loading points reduce the gross pollution of the atmosphere, but the best effect is obtained when the transfer point, where coal drops from one conveyor belt to another, is surrounded by a screen which reduces draughts and confines the spray.

In exceptional circumstances, where unlimited water can be used, a system of spraying into a duct counter-current to exhaust air carrying dust from a loading point has been used. This increases the velocity of impact and consequent suppression. Water can be collected and recirculated.

The main methods of suppression at the source which have been tried are water infusion, wet cutting with and without a wetting agent, the use of foam and dry drilling with air flush. Water used to quell dust must be delivered to the cutting edge through holes in the cutter. It is found, however, that high local temperatures developed at the cutting edge vapourise most

of it, allowing much of the dust to escape. To avoid this the tool is sometimes flushed with air instead of water, which is then drawn through a filter to remove the dust before being discharged to the atmosphere. If the resistances are adjusted so that the air line between the cutting edge and the filter is below atmospheric pressure, no dust should escape. Properly designed, a system of dry-drilling should be about 100 per cent effective.

If the rock is sufficiently porous it can, of course, be previously wetted, a process known as water infusion.

It has been found that, for dust not already airborne, effective application of water can be achieved only by the correct degree of atomization (41,42).

High efficiencies have been claimed for spray reduction of airborne dust concentration. In one case in an experimental mine gallery, an efficiency of 76 per cent was claimed for water and 80 per cent using wetting solution sprays (43).

In the past, attempts to knock down very fine dust particles by water droplets have not been markedly successful. Davies (44) has concluded that the most effective size for spray droplets is about 1,000 micron diameter, falling in still air, and these collide

with all dust particles of 20 microns and over which lie in their path. If, however, the dust particles are 5 microns. only 30 per cent of those in the path of the droplets are collected and carried to the ground, the other 70 per cent being displaced sideways by the air movement set up by the falling drop.

In order to improve the knockdown of small particles low surface tension solutions of wetting agents have been used (45, 46, 47). Results though showing a slight improvement on normal water suppressions are not impressive.

Price (48) employed a foam developed for fire fighting to reduce the amount of water used. Impressive results were claimed; but in pits, where more stringent conditions exist, the results obtained were inconclusive.

The Objects of the Programme of Research

Although much dust in pits can be suppressed at the source, no process is as yet 100 per cent effective and some, unhappily the potentially dangerous size-fraction, tends to escape, becoming an airborne hazard to health.

Much work has been done by the Monmouthshire and South Wales Coal Owners' Association, Coal Dust Research Committee (49), the U.S. Department of the Interior Bureau of Mines (50,51), and others on the suppression of dust at the source by sprays and the consolidation of roadway dusts (26,27,28), but very little work has been done on suppression of the dust once it is airborne (i.e. the fraction mainly below 5 microns) by aqueous sprays under controlled laboratory conditions.

Because of this lack of information it was decided to investigate the suppression of fine airborne dusts by aqueous sprays under controlled conditions. It was realised that before a spray nozzle could be used effectively to suppress an airborne dust a systematic study of a typical nozzle (i.e. its ability to atomise water and aqueous solutions) was necessary. The swirl atomiser was selected for study as being the simplest type of nozzle for use under mining conditions.

It was then hoped to extend the study to the atomisation obtained using aqueous solutions of surface-active agents with this type of nozzle. In the past the effect of surface-active agents on spray operation has been studied, but in general the agents used were complex compounds. It was thought that a better estimate of the effect of composition would be obtained by using simple compounds such as soaps and alcohols.

When the characteristics of the nozzles had been determined with water and aqueous solutions of surface-active agents it was proposed to study the effect of applied pressure, droplet size, spray velocity, and throughput on suppression. By correlating the results it was hoped to obtain an optimum value of droplet size effective against a range of particle sizes. The results obtained might also enable an "order of reaction" to be determined for the suppression process.

Although several quantitative airborne dust samplers exist none collects reasonable large samples quickly and accurately. It was decided that it would be of value to design a dust sampler which was portable, capable of use underground and of collecting a sample large enough for chemical analysis. On examination of

the methods of dust collection it was decided that an apparatus based on the Soxhlet paper filter thimble might be most suitable.

SECTION 1

Investigation of the Swirl Atomiser

The aim of atomisation in dust suppression is to divide a continuous jet of liquid into a spray of droplets in order to increase greatly the volume swept by the liquid. Atomisation may be achieved by merely forcing the liquid under high pressure through a small orifice into the atmosphere. Such a device is called a plain atomiser and the angle subtended by the spray cone is quite small because little tangential velocity is imparted to the liquid. Cone shaped sprays of wide angle are only produced if the liquid is given a marked tangential motion within the nozzle. Tangential motion may be obtained by forcing the liquid along a spiral path within the nozzle. Harvey and Hernandorfer (52), in a mathematical analysis of the flow of liquid in such nozzles, concluded that the tangent of half the spray cone angle was approximately equal to the ratio of the tangential velocity to the vertical velocity measured at the orifice.

The mechanism of atomisation has been studied by many workers in an attempt to derive a relationship between spray performance and the variables of an injection system. Spray performance may be considered in terms of :

(a) the throughput,

(b) the cone angle of the spray,

(3) the average droplet size,

(4) the droplet size distribution, and

(5) the energy requirements.

Rayleigh (53) submitted one of the first theories of liquid-jet disruption in a mathematical analysis of the stability of a non-viscous jet and his conclusions have been much used in later theories (54,55,56). Weber extended Rayleigh's analysis to the breakup of viscous liquids under forces of surface tension and air resistance, while Castleman in applying the same analysis to high velocity disturbances pointed out the similarity between pneumatic or air stream atomisation and pressure injection. Castleman further postulated the formation of ligaments at the liquid-gas interface which under the effect of surface tension collapse into droplets. Mehlig(57) and Schweitzer (58,59) stressed the importance of turbulent flow in the atomiser as an aid to the atomisation process. The turbulence was said by Mehlig to produce a radial component of fluid velocity which enabled the disintegrating jet to overcome the forces of surface tension. Thiemann(60) attributed the disintegration to the influence of the relative velocity between the outside of the liquid layer and the air itself whereas Oschats (61) believed the final atomisation of the jet to be dependent mainly on the

atmospheric resistance.

The disruption of liquid jets has been studied by means of high speed photography. The results obtained by Holfelder (62) and Haenlein (54) were confirmed theoretically by Webers' calculations for the initial stages of jet break up. Lee and Spencer (63) observed that ligament formation is controlled by the relative velocity between air and liquid. Ohnesorge (64) found jet stability to be a function of Reynolds number. Three or four stages of jet disintegration have been observed. The last stage of atomization is of greatest interest because it corresponds to the actual conditions of spray formation existing in injection systems. It is not known whether ligaments are formed at this stage as described by Castleman (55) and as observed by Scheubel (65), Nukiyama and Tanasawa (66) and Lee (67).

The action of the liquid viscosity and surface tension should theoretically have an effect on the disintegration of the liquid jet. Kuehn (68) in tests with jet injectors found that at high liquid velocities, corresponding to high pressures for pressure nozzles, droplet size was controlled by surface tension and inertia forces whereas at low velocities viscosity was found to be the controlling liquid property. A dimensional relationship was postulated by Scheubel (65)

in which droplet size varied inversely with viscosity. David (69) and Houghton (70) contended that an increase in viscosity results in a larger droplet size. High viscosity decreases the rate of breaking up of distortions of the droplets formed initially and increases the final droplet size. According to Hinze (71) in the initial stages of the development of surface distortions into ligaments and of the deformation of the droplets, the surface tension opposes the process but assists in the final stages of disruption. Since, however, the development of the initial stages of formation of the distortions is important for atomisation to proceed, an increase in the surface tension will cause a deterioration in atomisation. Klusener (72) and Littaye(73) also stressed the importance of surface tension in the atomisation mechanism.

Much work has been done in this field but many of the results obtained are somewhat conflicting. As a result no one has yet been able to give an accurate formula whereby it is possible to predict the expected performance of an atomiser of given dimensions. Neither is it possible to predetermine the exact effect of the viscosity and surface tension of the liquids used. Since it was necessary to obtain an estimate of the performance of the spray nozzles

used in this work before evaluating their suppression effect on airborne dusts the work to be described now was carried out.

Liquid Pressure Spray Units.

The nozzles used for the liquid pressure spray unit (Fig. 2.) were similar to those used in domestic swirl atomisers for spraying insecticides and they consisted of two parts, one screwing into the other. Water was forced between the two parts along a helical groove cut in the inner part, and out through the orifice drilled in the outer part. In order to determine the effect of orifice diameter, orifices of different diameters were drilled in eight nozzles as shown in Table 2. The same helical groove which was inclined at about 70° to the axis of the plug was used in all nozzles.

The pressure range investigated was up to 500 lb./in^2. For greater accuracy below 80 lb./in^2, a hand-operated commercial plunger-type pump fitted to a pressure vessel was used. As shown in Fig. 3. output passed by means of pressure rubber tubing to the spray nozzle via a needle valve which controlled the spray. The pressure tubing was connected by a T - piece to an accurately calibrated pressure gauge. Pressure was maintained by occasional manipulation of the plunger. This commercial pressure vessel had not been

FIGURE 2.

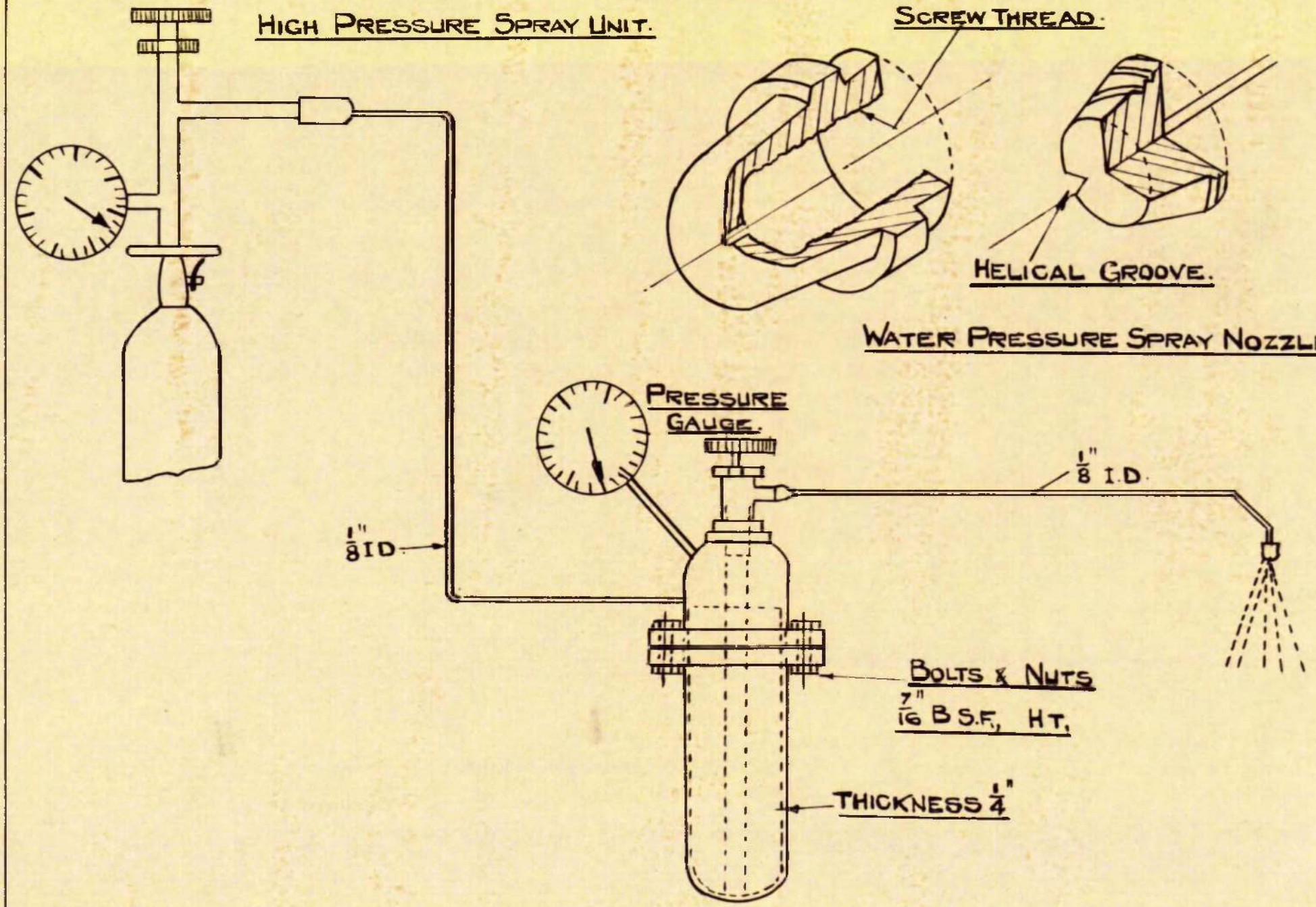

HIGH PRESSURE SPRAY UNIT.
SCREW THREAD.
HELICAL GROOVE.
WATER PRESSURE SPRAY NOZZLE.
PRESSURE GAUGE.
1/8 I.D.
1/8 I.D.
BOLTS & NUTS 7/16 B.S.F., H.T.
THICKNESS 1/4"

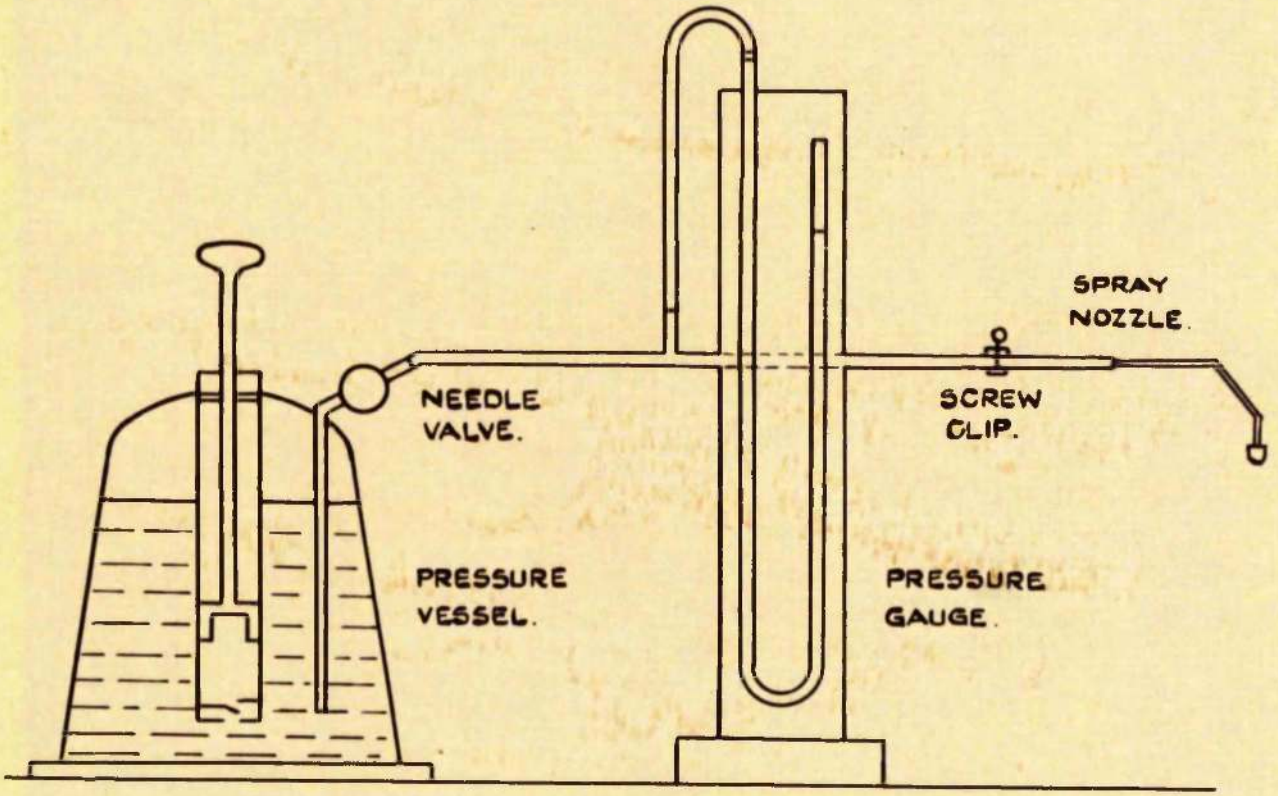
Table 2

Characteristics of Spray Nozzles

Nozzle	Orifice Diameter (d) ins.	$\frac{l}{d}$	Flow No. (Fn.)	Mean Coeff. of Discharge (c)	Cone Angle Deg.
A	0.0158	0.467	0.128	0.341	60
B	0.0161	0.610	0.139	0.360	60
C	0.0179	0.342	0.148	0.311	80
D	0.0356	0.149	0.239	0.126	90
F	0.0563	0.142	0.365	0.073	120
G	0.0897	0.134	0.530	0.044	130
H	0.1292	0.167	0.522	0.021	140
K	0.1608	0.172	0.777	0.020	160

FIGURE 3.

LOW PRESSURE SPRAY UNIT.



designed for pressures greater than 80 lb./in^2.

Higher pressures, i.e. above 80 lb./in^2., were obtained by means of compressed air applied to a thick walled cylinder containing the liquid to be atomised. For purposes of convenience and easy access the reservoir cylinder was made in two flanged parts as shown in Fig. 2. To prevent contamination of the liquid the vessel was fitted with a glass lining and the liquid to be atomised passed through a glass tube to a needle valve in the top of the vessel. All external pressure lines were of copper tubing. The spray pressure was indicated by a pressure gauge accurate to $\pm$ 1 lb./in^2. connected to the reservoir cylinder.

Sampling of Airborne Water Droplets.

In a study of the efficiency of atomisation in water jets some method of collecting and sizing the water droplets produced must be employed. Many different methods have been successfully tried for the measurement of droplet size. They can be divided into three main groups :-

(a) Direct Methods.

(b) Indirect Methods.

(c) The Method of Substitute Liquids.

Indirect methods can be divided into the following groups:-

(a) Photographic

(b) Photometric

(c) Electric

(d) Kinetic

(e) Thermal

In these indirect methods of droplet size estimation no attempt is made to measure the individual droplets and usuallly only a mean diameter can be determined. These mean diameters are based on a few measurements made on the bulk of the spray. As the sprays to be used were very heterogeneous some estimate of the droplet size distribution was required and these methods were therefore unsuitable.

The method of substitute liquids offers simplification of the counting technique but its use depends on whether the sizes of the droplets produced by the substitute liquid are the same as those in the real spray. The physical properties of the substitute liquid used would have to be close to those of the actual liquid. The method also involves the use of the microscope for droplets below 50 microns.

In the Direct Method of measurement, the spray droplets are caught on a target where they remain suspended while being counted and sized. In another modification of this method they leave an impression on a slide covered with a suitable

coating (e.g. magnesium oxide), from which, using a suitable correction factor, they can be counted and sized.

It was decided to employ both these latter techniques as they would give the required information on the spray from one set of measurements.

If too many droplets fall on the sampling area counting is difficult and aggregation may occur leading to errors. For this reason it is advisable to restrict the number of droplets falling on the sampling area by exposing for a short interval only.

Among the first workers to use as a target the so-called "immersion-liquid" were Hausser and Strobl in 1924 (74). This method has the advantage that, provided no splitting of the droplets occurs on hitting the liquid, the true droplet sizes are obtained and can be measured directly. It has two disadvantages in that it is time consuming and that it cannot be successfully applied to coarse sprays because large droplets hitting the liquid surface even at small distances still possess relatively high momentum which may cause them to split.

Rupe in 1949 (75) gave the following requirements for an immersion liquid :-

(a) The liquid must be absolutely immiscible with the

sprayed liquid.

(b) The density must be less than that of the sprayed liquid so that the drops will settle to a common plane for photography and yet must be high enough to prevent any appreciable flattening of the droplets.

(c) The viscosity must be low enough for the drops to penetrate the liquid without breaking up or evaporating and yet high enough to restrict convection and prevent movement and subsequent coalescence.

(d) The surface tension must be low in order to allow the small droplets to penetrate the surface.

(e) The vapour pressure should be low enough to prevent the formation of bubbles inside the cell.

(f) The liquid must have good light transmission. characteristics, be non-toxic and as nearly chemically inert as possible.

Experimental

The liquids investigated in the search for a suitable immersion liquid were paraffin-kerosene mixture (4:1 by volume), light kerosene S.G. 0.79, heavy kerosene S.G. 0.84, silicone fluid M.S.200/1,000 C.S., silicone fluid M.S.1107 and silicone fluid M.S. 550 (76). The physical characteristics of these liquids are shown in Table 3 overleaf.

Table 3.

Immersion Liquid	Viscosity centipoise at 20°C	Density g/ml at 20°C
Paraffin-Kerosene (4 : 1) by vol.	28.3	0.86
Light Kerosene	1.32	0.79
Heavy Kerosene	2.18	0.84
Silicone Fluid M.S. 200/1,000 C.S.	970	0.97
Silicone Fluid M.S. 1107	28.4	1.01
Silicone Fluid M.S. 550	114	1.07

Spraying was carried out with water at 50 lb./in.^{2} through nozzle A (Table 2.) and the samples were collected 18 ins. below the spray in a shallow (ca 2 ins. dia.) petri dish containing the immersion liquid. It was found that the droplets in each case fell to the foot of the liquid and flattened out losing their spherical shape. This was prevented by coating the foot of the petri dish with a layer of vaseline (77). It was found necessary to melt the vaseline and run it over the base of the dish to give a smooth layer free of air bubbles (see Fig. 4a). If the vaseline was unmelted it appeared under the microscope as shown in Fig. 4b; these included air bubbles made it necessary to melt the vaseline as above. Both large and small droplets

retained their spherical shape resting on the vaseline (see Figs. 4c and 4d) and could be counted and sized without the use of a correction factor.

The spray droplets were measured using an optical microscope with a low powered objective giving a magnification of X 100. The microscope eyepiece was fitted with a linear scale which had been calibrated from a stage micrometer.

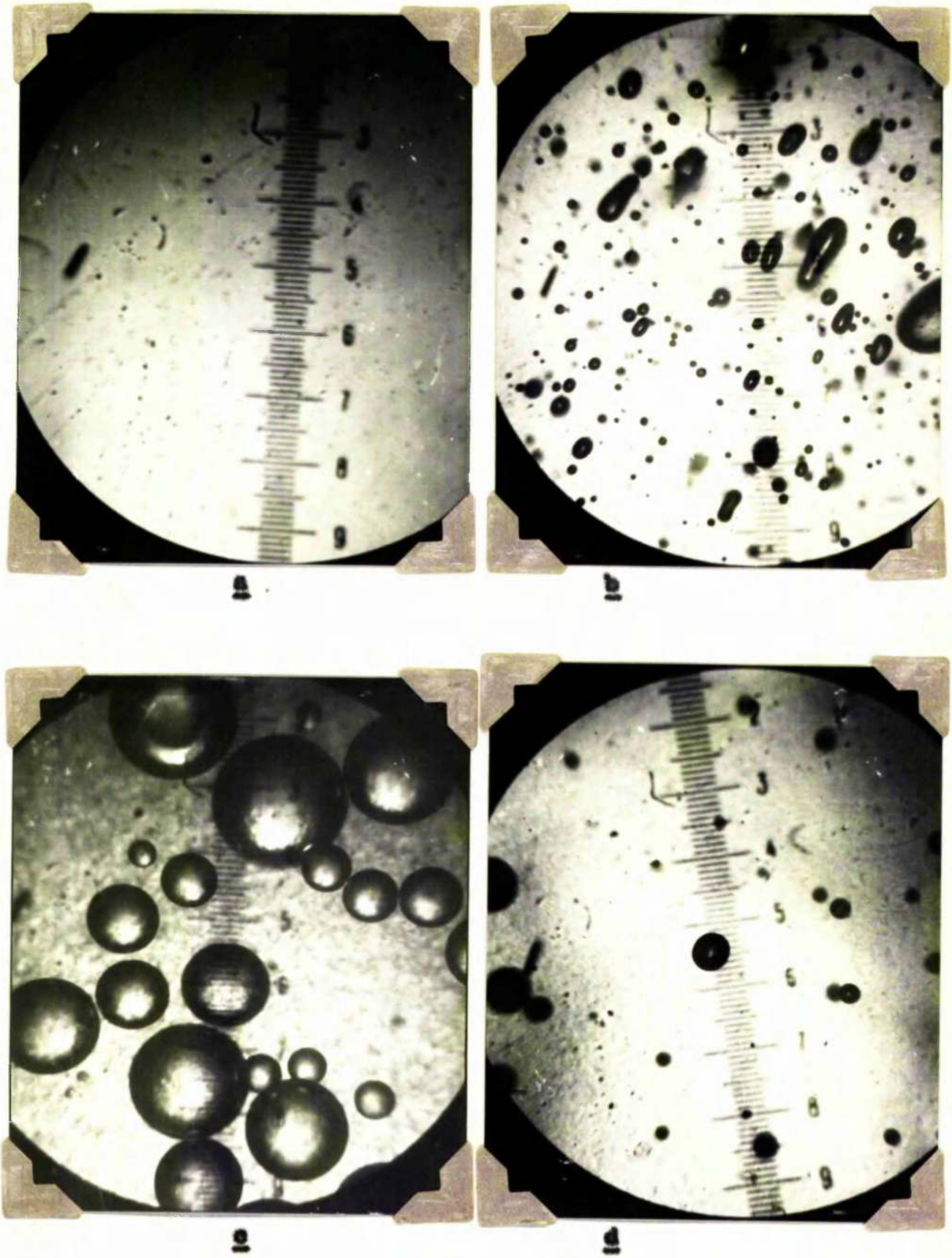
The average life of a droplet in the different liquids was taken as the time in seconds from the moment of formation to the instant when it visibly began to evaporate. An average life was got by determining the lives of 100 droplets of each size range.

Average Droplet Size

The sprays used did not give droplets of uniform diameter but a diameter variation over a wide size range. In a typical spray it was possible to find for example a small number of dropletswhich were about fifty times the size of the smaller droplets which ranged in size down to below 10 microns. It was therefore necessary to employ some average droplet size which would give an indication of the degree of atomisation and yet have a physical significance.

The introduction of such an average droplet size is

FIGURE 4



a

b

c

d

equivalent to the replacement of the actual spray of wide size range by a theoretical spray composed of droplets which are all of the same size equal to the average droplet size. This spray will still, however, possess certain features of the actual spray which are important from the point of view of dust suppression. Sauter (78), in analysing the requirements of a spray for an internal combustion engine, defined the spray fineness by comparing it with a fictitious uniform spray composed of droplets of uniform size and having the same total droplet surface and volume as the actual spray. Other workers have used various average droplet size diameters such as Geometric Count Average, Geometric Weight Average, Arithmetic Average, Surface Average, Volume Average, Specific Surface and Surface-per-unit-volume. Hatch (79) and Choate (80) derived relationships between these average droplet diameters. The one which lends itself most readily to this method of estimating droplet size and which was used throughout this work is the arithmetic average or arithmetic mean diameter, hereafter referred to as A.D.S. This is a function of the number (N) and the diameter (D) of the droplets and is represented by $\sum(ND)/\sum N$. It is important in this work since the projected diameter of the droplet is one of the determining factors in its chance encounter with a dust

particle.

It was found necessary to count 400 droplets for each value and this was done by counting 50 droplets in each sample, i.e. eight samples were taken for each liquid in order to eliminate as far as possible errors due to evaporation and aggregation of the droplets.

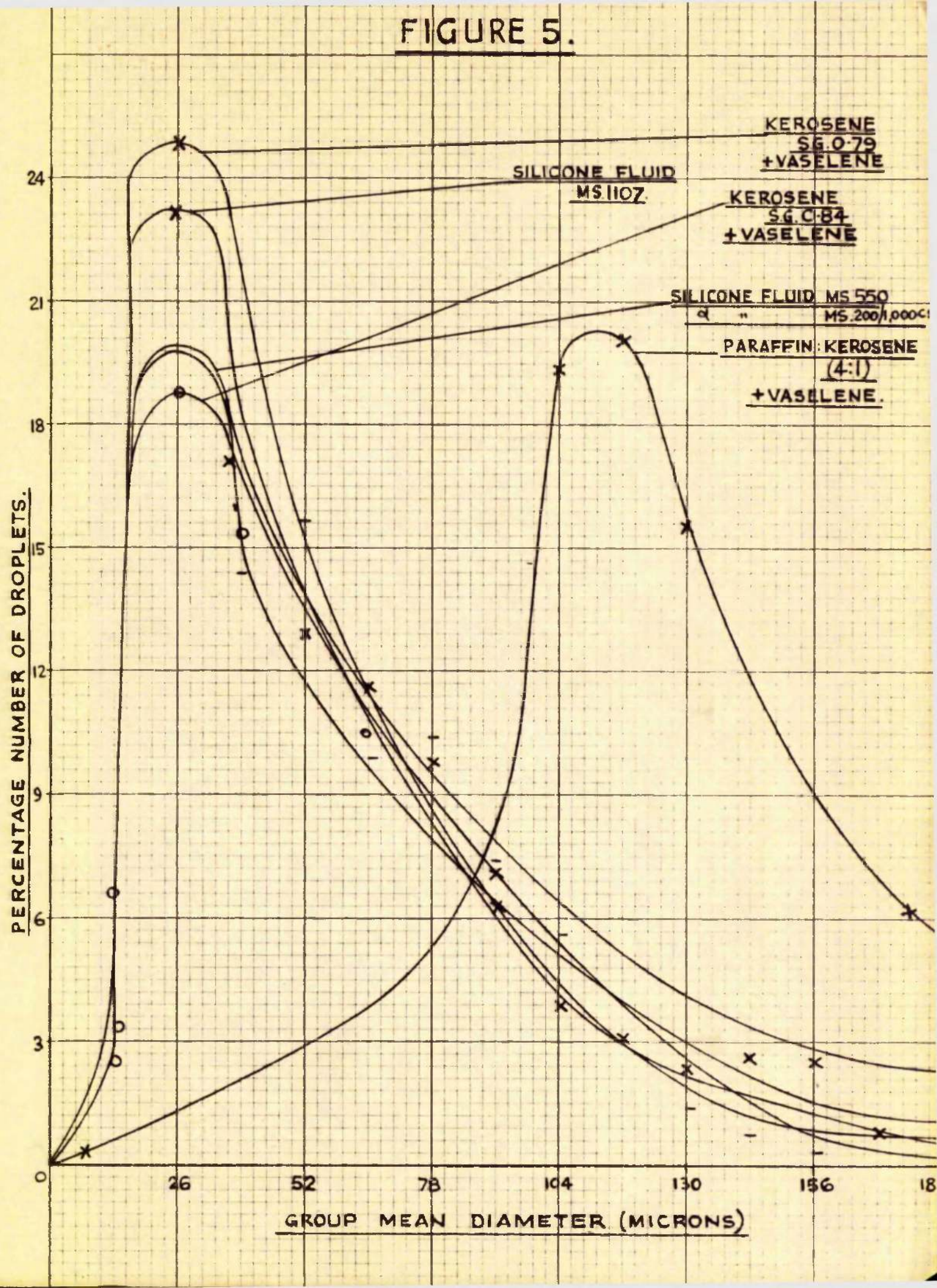
Experimental Results

The droplet size distribution curves for samples of droplets collected on all six liquids are shown in Fig. 5. Except for that obtained for the paraffin-kerosene mixture the curves are similar. The A.D.S. calculated for the paraffin-kerosene mixture is also high as shown in Table 4. This may perhaps be due to the mixture being too viscous for all the smaller droplets to penetrate.

Table 4.

Sampling Fluid	A.D.S. Microns
Paraffin-Kerosene (4:1) by vol.	65.5
Light Kerosene	61
Heavy Kerosene	65.5
Silicone Fluid M.S. 200/1,000 C.S.	63.5
Silicone Fluid M.S. 1107	48
Silicone Fluid M.S. 550	58.2

FIGURE 5.


KEROSENE S.G. 0·79 +VASELENE
SILICONE FLUID MS 1107
KEROSENE S.G. 0·84 +VASELENE
SILICONE FLUID MS 550
" MS. 200/1,000
PARAFFIN: KEROSENE (4:1) +VASELENE.
PERCENTAGE NUMBER OF DROPLETS.
0
3
6
9
12
15
18
21
24
26
52
78
104
130
156
GROUP MEAN DIAMETER (MICRONS)

If it was suspected that the sampling fluid did not allow the smaller drops to penetrate or kept the droplets near the surface promoting evaporation more than eight samples were taken to give a better size distribution and average droplet size.

In heavy kerosene a higher A.D.S. was obtained, this may again be due to the effects of viscosity. The peak of the droplet-size distribution curve for this liquid was lower than that obtained with the other liquids. With light kerosene very good samples were obtained, all droplets penetrating and retaining their spherical shape for some considerable time. The size distribution curves obtained for silicone fluids M.S. 550 and M.S. 200/1,000 C.S. were almost identical; however, the average droplet size varied. The droplets could hardly be said to penetrate the silicone fluids but actually remained suspended near the surface with consequent continuous evaporation.

The average lives of droplets from 7 microns to 195 micronsfor silicone fluids M.S. 550, M.S. 1107 and M.S. 200/1,000 C.S. are plotted on Fig. 6. Since it took 15 seconds from time of sampling to beginning of count, very few droplets below 14 micronswere counted unless a large number of samples was taken.

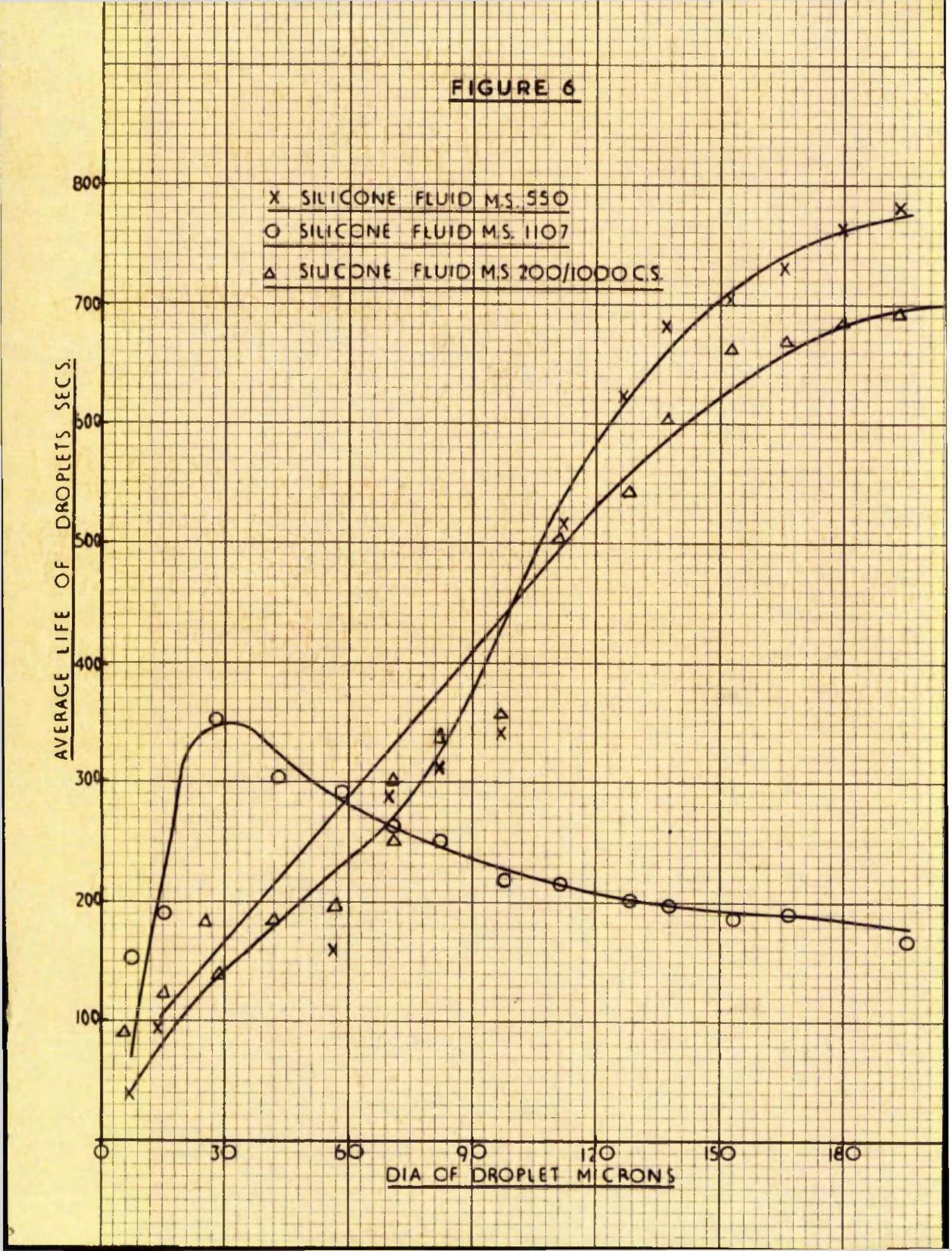


FIGURE 6
X SILICONE FLUID M.S. 550
O SILICONE FLUID M.S. 1107
Δ SILICONE FLUID M.S 200/1000 C.S.
AVERAGE LIFE OF DROPLETS SECS.
800
700
600
500
400
300
200
100
0
30
60
90
120
150
180
DIA OF DROPLET MICRONS

With light kerosene it was found that all droplets observed lasted for at least 12 minutes.

It would therefore appear that the only immersion liquid which satisfies the required properties is light kerosene (specific gravity 0.79, viscosity 1.32 centipoise). This sampling fluid allows ample time to count 50 drops on each sample. It has the lowest viscosity of the fluids tried allowing droplets to penetrate the liquid without breaking up or evaporating and yet high enough to prevent too much movement of the droplets with subsequent coalescence. Its surface tension is low enough to allow the smaller drops to penetrate the surface. Since the density is less than that of the sprayed liquid, the droplets settle to a common plane enabling counting to be done by microscope. It is absolutely immiscible with the sprayed liquid and its vapour pressure is low enough to prevent the formation of bubbles during counting. The important point of good light transmission qualities is also satisfied.

The fluid was used throughout the following work with a melted layer of vaseline on the base of the dish to prevent spreading of the droplets.

Effect of Applied Pressure on Throughput in Swirl Atomiser

Schweitzer (81) believed the flow in an atomiser orifice

to be similar to that in a pipe and dependent on Reynolds number. Maximum atomsiation is obviously to be obtained in the region of turbulent flow. Assuming the viscous losses to be negligible, a swirl atomiser should therefore behave like a plain atomiser, the flow varying as the square root of the applied pressure.

The throughput for each liquid-pressure nozzle was measured by spraying vertically downwards into a graduated cylinder for a sufficient length of time to ensure reasonable accuracy. This procedure was repeated at 21 different values of applied pressure over the range 5-500lb./in^2. A plot of the results in Table 5 shows a linear relationship between the throughput V in gallons per hour against the square root of the pressure up to 500lb./in^2. as shown in Fig. 7. Doble (82) denoted the gradient of this line by the symbol K; it has also been called the flow number Fn by Watson and Clarke (83). Previous work (84) showed that the throughput is not affected to any appreciable extent by using solutions of surface active agents having a surface tension as low as 25 dynes/cm.

The results of Table 5 indicate that the following normal formula holds:

$$q = Ac\,(2gP/p)^{\frac{1}{2}}$$

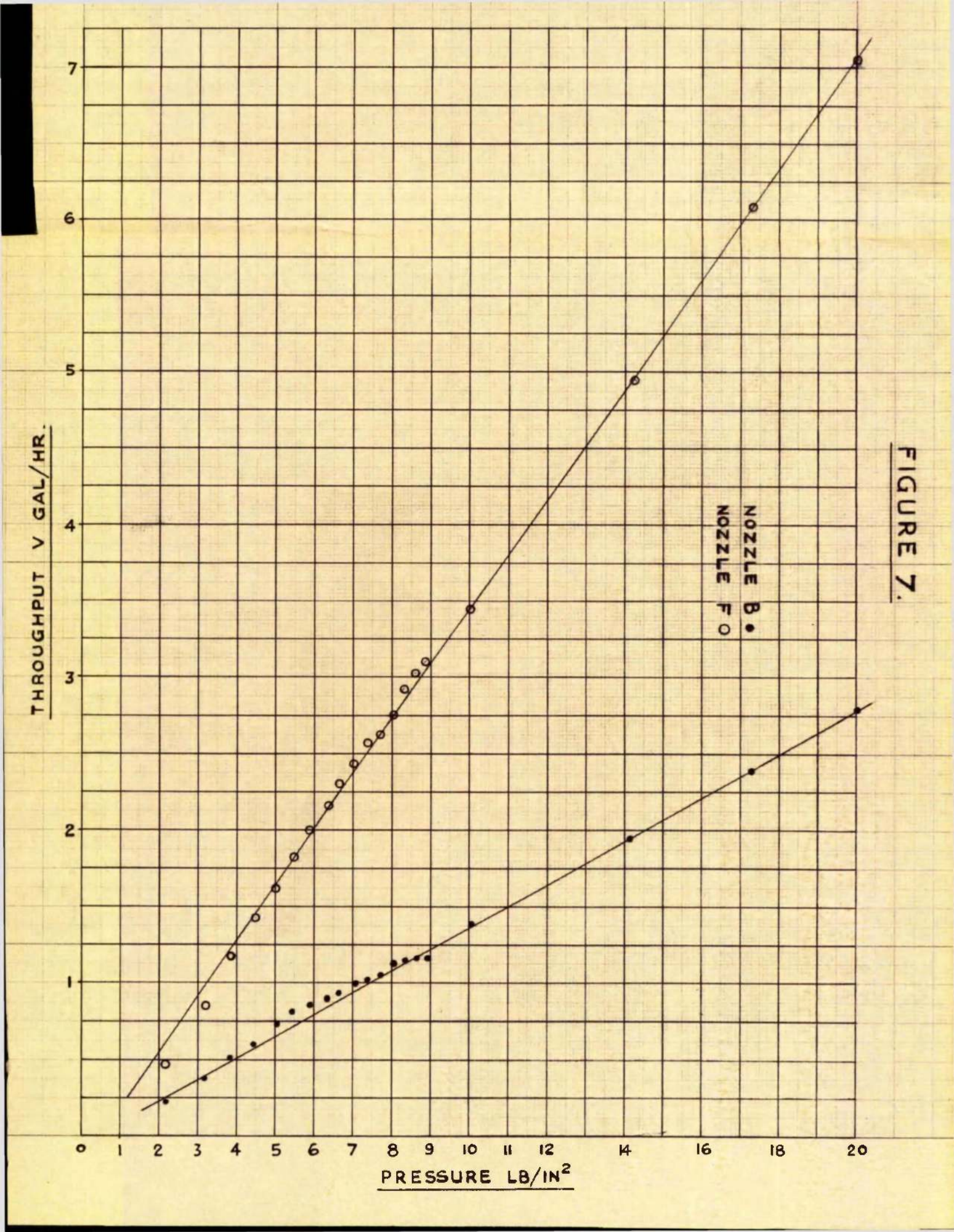

THROUGHPUT V GAL/HR.
PRESSURE LB/IN²
NOZZLE B •
NOZZLE F ○
0 1 2 3 4 5 6 7 8 9 10 11 12 14 16 18 20
1 2 3 4 5 6 7

FIGURE 7.

Table 5
Throughput Gall./Hr.

Pressure lb./in²	Nozzle A	Nozzle B	Nozzle C	Nozzle D	Nozzle F	Nozzle G	Nozzle H	Nozzle K	P
5	0.2436	0.2219	0.2312	0.3493	0.4833	0.5051	0.5214	0.7030	2.236
10	0.3858	0.3924	0.4337	0.6401	0.8612	1.066	1.155	1.6110	3.162
15	0.4950	0.5313	0.5610	0.8845	1.169	1.496	1.674	2.416	3.873
20	0.5940	0.6006	0.6601	1.046	1.432	1.828	2.079	2.891	4.472
25	0.6733	0.7261	0.7365	1.212	1.628	2.138	2.409	3.089	5.00
30	0.7261	0.7854	0.8448	1.326	1.832	2.376	2.799	3.419	5.477
35	0.7723	0.8580	0.9042	1.436	2.017	2.643	3.036	3.808	5.916
40	0.7987	0.9042	0.9768	1.531	2.163	2.859	3.274	4.264	6.325
45	0.8674	0.9570	1.030	1.630	2.310	3.023	3.531	-	6.708
50	0.9307	1.001	1.082	1.683	2.442	3.207	3.657	4.70	7.071
55	0.9504	1.036	1.126	1.762	2.574	3.339	3.907	-	7.416
60	0.9636	1.086	1.161	1.835	2.614	3.478	4.052	5.17	7.746
65	1.056	1.122	1.188	1.947	2.746	3.796	4.277	-	8.062
70	1.069	1.135	1.227	2.013	2.917	3.991	4.462	5.44	8.367
75	1.096	1.155	1.274	2.072	3.009	4.014	4.594	-	8.660
80	1.148	1.175	1.293	2.125	3.102	4.066	4.639	6.17	8.944
100	1.28	1.39	1.48	2.40	3.42	4.72	5.20	7.20	10.0
200	1.81	1.96	2.09	3.38	4.93	6.84	7.35	9.80	14.142
300	2.21	2.41	2.58	3.16	6.10	8.50	8.98	13.40	17.321
400	2.57	2.79	2.96	4.80	7.05	9.98	10.40	14.65	20.0
500	2.85	3.16	3.38	5.39	7.91	11.35	11.68	18.05	22.36

where g is the throughput in cubic feet per second, A the cross sectional area of the nozzle orifices in square feet, c the discharge coefficient of the nozzle, g the gravitational constant in feet per second square, P the applied pressure in lb per foot square and p the density of the liquid in lb per cubic foot. However, if q is measured in gallons per hour, A in inches square, P in lb./in.^{2}, g is 32.2 ft./sec.^{2} and p is 62.4 lb./ft.^{3} the formula becomes :

$$q = 1902\ AcP^{\frac{1}{2}}$$

$$\therefore F_n = qP^{-\frac{1}{2}} = 1902\ Ac$$

The coefficients of discharge of the various nozzles are given in Table 2 as calculated from the above formula.

It has been suggested by Gelalles (85,86,87) and Joachim (88) that the coefficient of discharge of an atomising orifice depends on the Reynolds number (Re) of the flow in the orifice and on the ratio of the length of the nozzle to the diameter (l/d). The coefficient of discharge is at low velocities a complicated function of Reynolds number (hereafter referred to as Re) becoming virtually constant in the turbulent region. Re as calculated is not, however, the true value for flow in the nozzle. This is because V the fluid velocity used in the calculation is only a mean axial velocity,

even if the orifice runs full and in the case of swirl atomisers an air core usually exists so the value of d, the orifice diameter, is incorrect. The value of Re obtained is, however, of some value as it depends on the same quantities as the true Re. The coefficients of discharge have been calculated over the full pressure range for two nozzles B and F and are shown as coefficient of discharge plotted against throughput and Re in Figures 8 and 9. Low values of coefficient of discharge are normally associated with swirl atomisers.

Other workers (87,89,90) found the coefficient of discharge to increase rapidly at low values of Re, gradually levelling out before an irregularity appeared in the curve. Following the irregularity the curves showed a fairly constant value of coefficient of discharge with increase of Re. This is also apparent in Figures 8 and 9, the coefficient of discharge increasing rapidly to Re = 2000 in the case of nozzle B and 6000 in the case of nozzle F. The curves can be divided into three stages, the first corresponding to laminer flow over a range of Re = 0 - 2000 (Fig. 8) or Re = 0 - 6000 (Fig. 9). The second might be related to semi-turbulent flow and shows at first an increase followed by a decrease of discharge coefficient. The third stage

FIGURE 8

NOZZLE B.

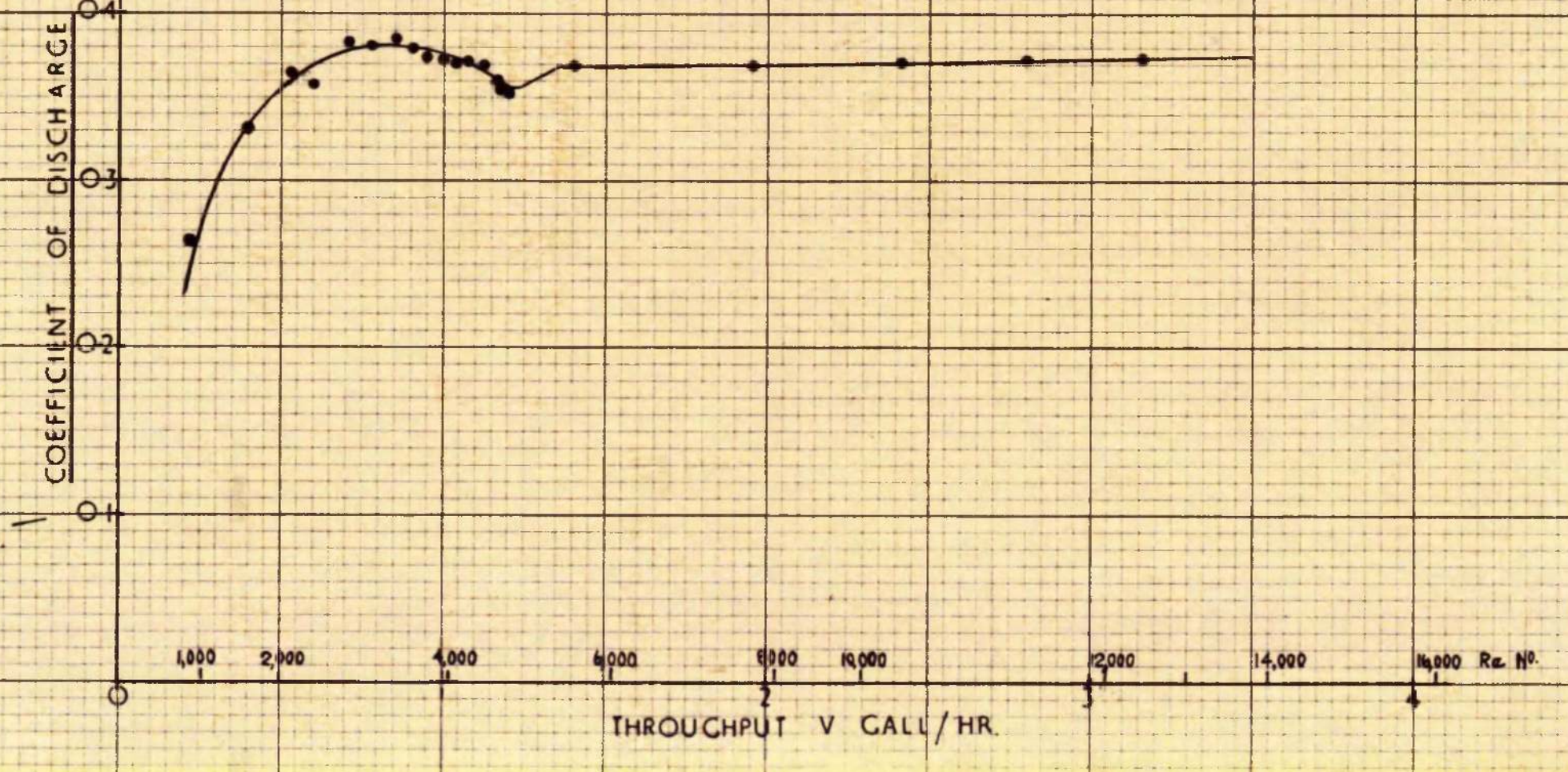
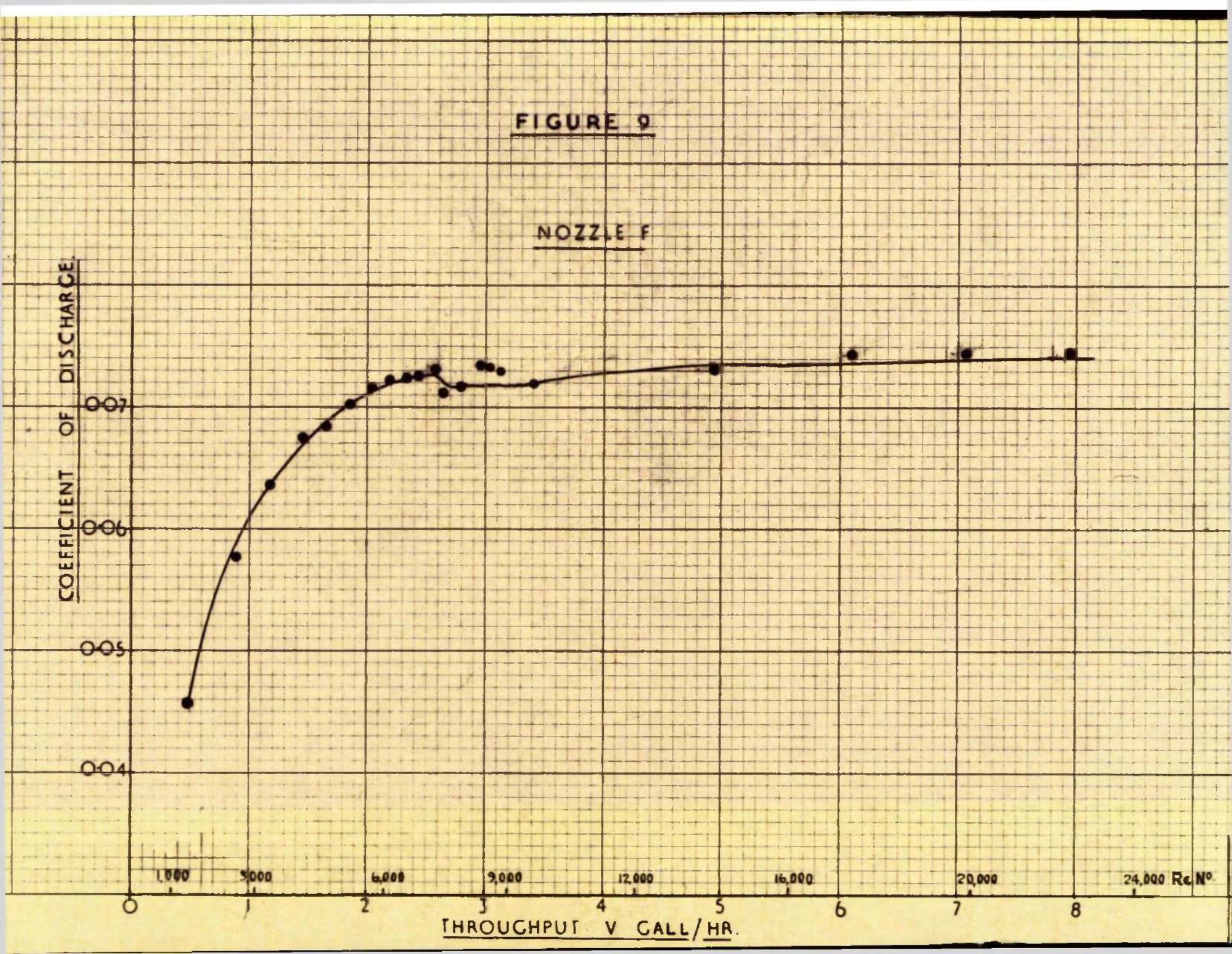


FIGURE 9

NOZZLE F



would appear to correspond to turbulent flow and the discharge coefficient in this section appears almost constant.

Giffen and Massey (91) using perspex nozzles showed that the air core in a helical grooved nozzle is formed suddenly, and as the efflux area is reduced by the formation of an air core the coefficient of discharge will fall. This sudden irregularity can be seen in Figures 8 and 9 and it is probable that the air core is being formed at that value of Re.

Increase in the coefficient of discharge can be explained as the result of friction losses in the atomiser decreasing both the tangential and the axial velocities. Decrease in the tangential velocity means a decrease in the swirl and hence a decrease in the diameter of the air core, so that the effective area for flow through the orifice becomes greater. When the air core becomes very small changes in diameter have very little effect on the flow area. Thus the coefficient of discharge should decrease with increase in orifice diameter less friction loss being encountered the larger the orifice opening. This is shown to be the case in Table 2.

Effect of Pressure on Droplet Size

Six nozzles were investigated to find the range of

droplet size obtainable by altering the applied pressure. Samples were collected at distances of 18 ins. and 48 ins. from the orifice of all nozzles and also at 8 ins. from the orifice in the case of nozzle A. The results expressed as Arithmetic Mean Diameters are given in Tables 6. and 7. The results are in general agreement with previous work (92,93,94,95, 96,97). Atomisation as expressed by average droplet size increases with rise in pressure more rapidly at low pressures. At high pressures an increase in injection pressure gives a less marked decrease in droplet size. The improvement of atomisation with increased injection pressure generally consists not in a decrease in the size of the smallest droplets(ca 6 microns)but in an increase in the number of small droplets and a decrease in the size of the large droplets i.e. in a greater spray uniformity as can be seen from Figure 10.

The effect of injection pressure on the spray cone angle is not appreciable provided the pressures are already high enough to produce a fully developed spray cone.

Effect of Orifice Diameter on Droplet Size

Earlier work on plain and swirl atomisers by Gelalles (85), Lee (95,97), Joyce (96) and Sass (98) has indicated that an increase in orifice diameter decreases the degree of

Table 6

Average Droplet Sizes (microns) 8 inches from Nozzle

Applied Pressure (lb./in.^{2})		10	15	20	25	30	40	50	60	70	80	150	250	400	500
Nozzle	A	294	217	164	118	113	66.0	60.0	45.0	38.5	35.2	34.4	27.2	24.0	20.9

Average Droplet Sizes (microns) 18 inches from Nozzle

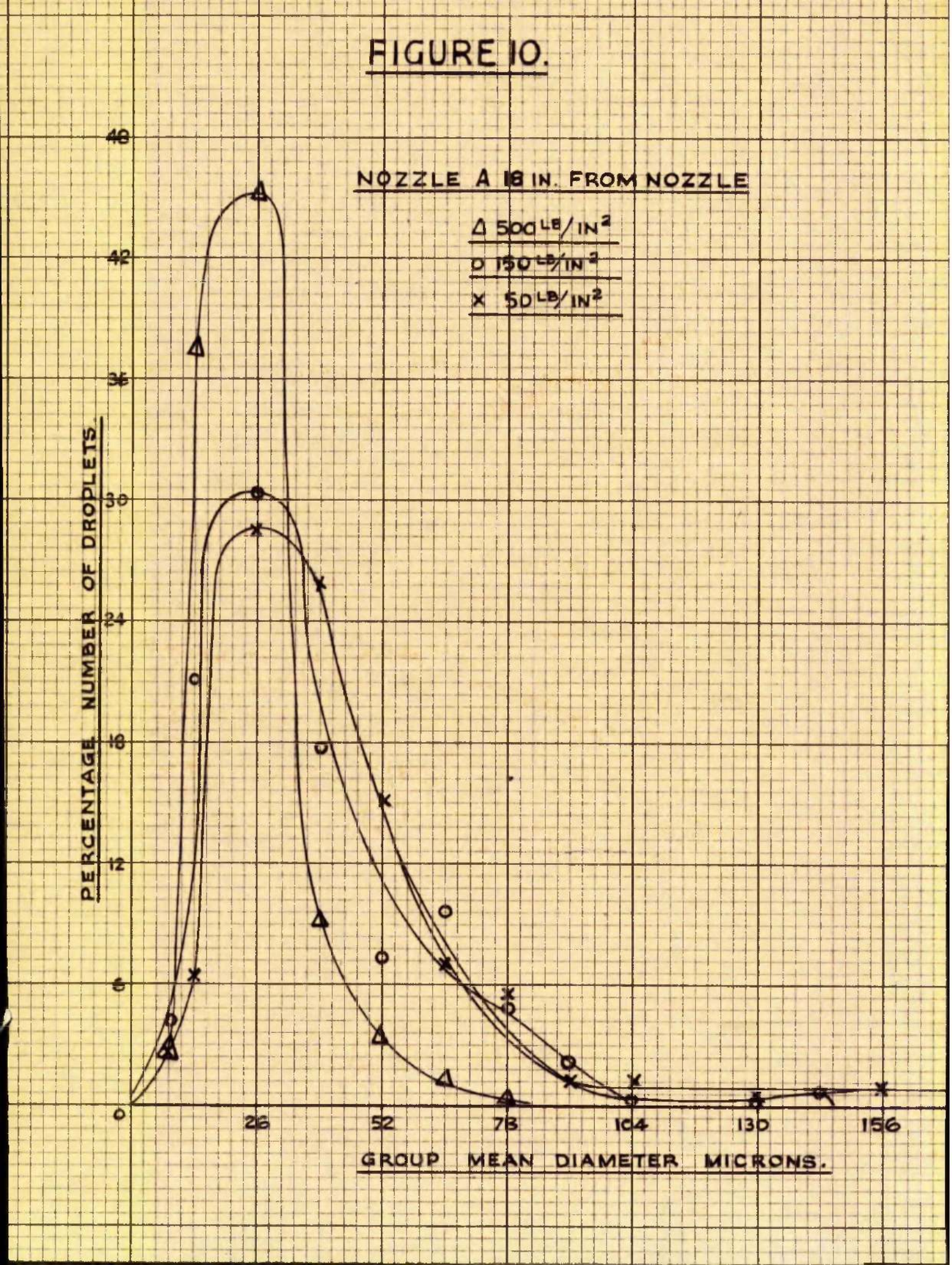
Nozzle	A	284	201	173	111	66.8	70.8	55.1	56.6	45.0	46.2	38.4	34.2	28.1	24.9
	B	344	227	128	92.7	80.7	62.5	64.6	55.9	54.5	45.8	39.8	34.6	31.8	29.7
	C	443	341	206	176	136	102	57.1	53.6	46.8	47.6	46.5	33.0	28.8	23.2
	D	626	270	166	89.0	63.8	77.6	42.9	53.7	42.7	38.2	39.2	31.9	27.6	24.6
	F	465	278	248	182	136	88.8	78.4	62.5	60.0	51.1	45.8	42.0	37.4	33.0
	G	667	397	238	194	143	104	88.0	69.8	59.4	65.6	46.6	45.6	39.6	36.1

Table 7

Average Droplet Size (microns) 48 inches from Nozzle

Applied Pressure (lb./in²)		10	15	20	25	30	40	50	60	70	80	150	250	400	500
Nozzle	A	216	158	123	109	90.5	80.0	78.2	72.6	66.0	65.0	47.3	43.8	41.0	38.2
	B	352	247	150	110	101	95.0	83.7	71.5	78.7	79.0	68.3	61.1	54.3	49.6
	C	360	184	160	132	98.5	68.4	92.0	60.1	71.0	74.6	62.0	60.4	57.2	55.0
	D	362	229	182	156	119	85.6	62.5	59.6	57.4	68.5	47.2	55.6	47.8	53.5
	F	461	288	222	188	127	124	73.5	108	86.8	77.2	82.0	74.6	70.5	61.6
	G	595	392	268	203	177	118	72.2	64.2	80.5	51.7	55.2	48.2	47.0	46.4

FIGURE 10.


NOZZLE A 18 IN. FROM NOZZLE
Δ 500 LB/IN²
○ 150 LB/IN²
× 50 LB/IN²
PERCENTAGE NUMBER OF DROPLETS
48
42
36
30
24
18
12
6
0
26
52
78
104
130
156
GROUP MEAN DIAMETER MICRONS.

atomisation. The contact surface between jet and air (i.e. orifice circumference X liquid velocity) with a plain atomiser increases more slowly with increase in orifice diameter than the volume of liquid discharged (i.e. orifice cross section X liquid velocity) and thus atomisation decreases. The picture with swirl atomisers is more complex, other factors coming into play. A change in orifice diameter will affect the ratio of l/d which in turn will affect the cone angle of the spray as shown in Table 7. In a swirl atomiser the degree of atomisation obtained is very dependent on cone angle. A wide-angle spray gives greater surface contact between liquid and air but the change in the cone itself is the result of increased tangential and radial velocities which assist disintegration of the droplets. Thus any change in atomisation brought about by change in orifice size is the resultant of two related variables ; (a) the ratio of the cross section of the orifice to its circumference and (b) the ratio l/d. Atomisation may increase or decrease according to their relative values.

From Table 6 it can be seen that at the lower pressures the average droplet size increases with orifice diameter. At higher pressures however when liquid velocity is greater

atomisation does not necessarily decrease with increase in orifice diameter. With nozzle B which has a larger orifice diameter than nozzle A and the same cone angle a slightly higher average droplet size is obtained. Nozzle C whose orifice diameter is greater again but whose cone angle is also larger gives a smaller average droplet size than either nozzle A or B. It seems that the effect of an increase of 20° in cone angle for this nozzle with subsequent increase in surface contact between liquid and air has overcome the effect of the increase in orifice diameter. In fact, nozzle C seems to give the lowest average droplet size of all the nozzles tried and it is possible that it has the best combination of variables as far as the production of a small droplet size is concerned. It can be seen from the rest of the table that the effect of further increasing the orifice diameter is to decrease the atomisation despite further consequent increase in cone angle.

Determination of Laws Connecting Pressure and Average Droplet Size

Dimensional analysis has been employed by many workers as it offers a suitable means of utilising and correlating existing information. Dorman (99) used it to derive an equation relating a mean droplet diameter to the operating conditions of the nozzle for a flat spray. In their study

of atomisation by different methods Fraser, Eisenklam and Dombrowski (100) employed the expression

$d \propto \left(\frac{Fn}{\Delta P \theta}\right)^{\frac{1}{3}} \left(\frac{\rho_L}{\rho_A}\right)^{\frac{1}{2}}$ derived by dimensional analysis which in general relates the properties of the liquid and the atomiser, where d is a mean diameter of the spray, Fn the flow number of the atomiser for a standard liquid, ΔP the pressure differential, γ the surface tension of the liquid, θ the cone angle, ρ_L the density of the liquid and ρ_A the density of the atmosphere. If we consider a single liquid in air and a single orifice the expression will reduce to :

$d \propto K_1 \Delta P^{-\frac{1}{3}}$ where $K_1 = \left(\frac{Fn\gamma}{\theta}\right)^{\frac{1}{3}} \left(\frac{\rho_L}{\rho_A}\right)^{\frac{1}{2}}$

or $d = KP^{-\frac{1}{3}}$

Different investigators such as Joyce (96), Needham (101) and Muraszew (102) have given formulae which are in some cases only applicable to a limited set of conditions. This was of the type mean diameter $= KP^{n}$ and Needham (101) found the index n to have a value of -0.275 whereas Joyce (96) obtained a value of -0.35. These formulae were derived from results of experiments with swirl atomisers using molten wax. Using different types of nozzles, both swirl

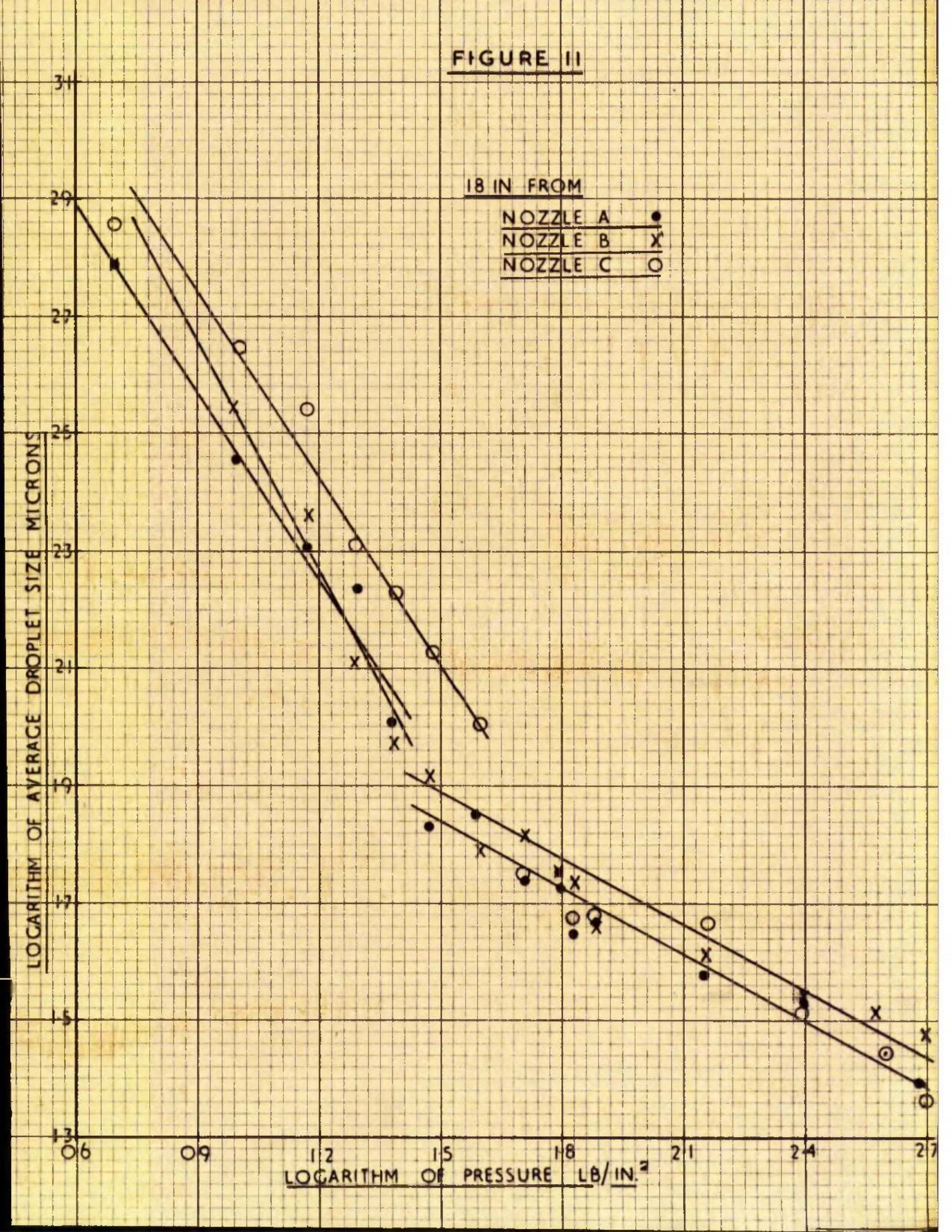
and plain, Muraszew (102) found a mean value of 0.42. However, as he included plain atomisers in the determination of a mean value, the value he obtained will be higher than for the swirl types. Another factor which may account for some of the difference between reported figures is that different methods have been employed for droplet measurement.

If the law $d = KP^{-1/3}$ (where K is a constant and P the applied pressure) derived above for a single nozzle with a specific liquid is applicable to the results obtained a straight line should be obtained of slope -0.33 when log A.D.S. is plotted against log of P. This plot for nozzles A, B and C sampled at 18 ins. from the nozzle is shown in Fig. 11. Above about 30 lb./in.^{2} the slope of the lines is approximately - 0.33 agreeing with the value obtained by dimension of analysis. Values of the gradient above and below the change point at 18 ins. and 48 ins. from the nozzle are tabulated in Table 8 below.

Table 8

Nozzle	Sampled 18 ins. from nozzle		Sampled 48 ins. from nozzle	
	Gradient		Gradient	
	Below 30lb/in.^{2}	Above 30lb/in.^{2}	Below 30lb/in.^{2}	Above 30lb/in.^{2}
A	-0.98	-0.38	-1.12	-0.31
B	-1.26	-0.36	-1.30	-0.24
C	-1.05	-0.36	-1.20	-0.10
D	-1.60	-0.37	-1.00	-0.085
F	-1.01	-0.32	-0.94	-0.14
G	-2.00	-0.32	-1.20	-0.21

FIGURE 11


18 IN FROM
NOZZLE A •
NOZZLE B X
NOZZLE C O
LOGARITHM OF AVERAGE DROPLET SIZE MICRONS
31
29
27
25
23
21
19
17
15
13
06
09
12
15
18
21
24
27
LOGARITHM OF PRESSURE LB/IN.²

At 18 ins. in all cases at high pressure, i.e. above about 30 lb./in.^{2}, the value obtained is $\underline{m}$ - 0.33. Below this pressure and at 48 ins. from the nozzle varying values were obtained. This may be explained by the wide range of droplet size and consequent inaccuracy in determining the A.D.S. obtained at low pressures 18 ins. from the nozzle. At 48 ins. the change of A.D.S. with distance from the nozzle (see page 47) would account for the variation. In general the most reproducible figures for atomisation are obtained above 30 lb./in.^{2} and any actual dust spraying is done above this pressure so the value of - 0.33 represents the most relevant figure. The value of n appears to decrease as the diameter of the orifice increases.

It is therefore possible to measure experimentally the average droplet size obtained at two pressures (e.g. 50 lb./in.^{2} and 500 lb./in.^{2}), draw the straight line, and measure the values of K and n of the equation of the curve for any nozzle. Thus an approximate prediction of droplet size may be made and may save some of the usual lengthy procedure of droplet measurement.

Relationship Between Energy Supplied and Energy used in Atomisation

It is useful to calculate the energy supplied for atomisation with pressure injection and compare it with the

minimum energy necessary for atomisation. It is possible to calculate these energies using the approach suggested by Giffen and Muraszew (103). The pressure energy supplied, Ep in ft. lb./lb. is given by the relationship

$$Ep = P/p$$

where P is the applied pressure drop in lb./ft.^{2} and p is the liquid density in lb./ft.^{3} Thus, where the applied pressure is measured in lb./in.^{2} and only water and dilute aqueous solutions are being atomised at room temperatures, the equation reduces to

$$Ep = 144P/62.4 = 2.31P \text{ ft. lb./lb.}$$

The energy required for atomisation is the product of the surface tension of the liquid and the increase in surface area per unit weight. It can be expressed as

$$Ea = \gamma (A_2 - A_1)/p$$

where A_1 and A_2 are the surface areas of 1 c.c. of liquid before and after atomisation respectively and γ is the surface tension of the liquid in dynes/cm.

For a liquid of unit density a 1 c.c. sphere has a surface of 4.84 cm.^{2} but if this sphere is divided into droplets of diameter 25 microns the total surface area is now 2400 cm.^{2} It can be seen that the surface area of the liquid before atomisation is negligible compared to that of the liquid after

atomisation and if a rapid approximate estimation of the energy required for atomisation is made the above relationship can be simplified to the form

$$Ea = \gamma A_2 = 3 \gamma V/r_2 = 60{,}000 \gamma / D \text{ ergs/gm}$$

where r_2 is the droplet radius, D the droplet diameter in microns and V is 1 c.c.

This may be compared directly with the pressure energy E_p by converting to suitable units, thus

$$Ea = 60{,}000 \gamma / 29{,}900 D = \frac{cm}{}, \ 2 \gamma / D \text{ ft. lb./lb.}$$

The approximate values of Ea and E_p for the nozzles are listed in Table 9. The values of Ea were calculated from the average droplet size values obtained by drawing the best curve through the experimental points. It can be seen that although Ea increases with E_p, it is much lower than expected. In reality only a small part of the energy is used for atomisation of the liquid, the majority being imparted to the air in the path of the spray or converted into thermal energy. The relationship between Ea and E_p can be obtained from the derived expressions $E_p = 2.31 P$, $Ea = 2\gamma/D$ and $D = kP^{-\frac{1}{n}}$

$$\therefore Ea = k^1 E_p^{\frac{1}{n}} \quad \text{where } k^1 = \frac{2\gamma}{2.31 k}$$

n has already been tabulated in Table 8. A plot of Ea vs. E_p for nozzles A and B sampled 48 ins. from the nozzle

Table 9

Sampled at 18 ins. from nozzle

Nozzle	A			B		C		D		F		G	
Pressure lb./in.^{2}	Ea ft.lb./lb.	Ep	100Ea/Ep	Ea ft.lb./lb.	100Ea/Ep	Ea ft.lb./lb.	100Ea/Ep	Ea ft.lb./lb.	100Ea/Ep	Ea ft.lb./lb.	100Ea/Ep	Ea ft.lb./lb.	100Ea/Ep
5	0.187	11.55	1.62	0.23	2.01	0.185	1.60	0.090	0.77	0.03	0.25	0.024	0.21
10	0.29	23.1	1.26	0.40	1.74	0.31	1.34	0.22	0.94	0.29	1.27	0.05	0.23
15	0.42	34.65	1.21	0.70	2.02	0.49	1.42	0.52	1.48	0.47	1.36	0.35	1.05
20	0.80	46.2	1.74	1.11	2.38	0.68	1.47	0.93	2.00	0.64	1.39	0.586	1.27
25	1.31	57.75	2.27	1.53	2.64	0.85	1.48	1.27	2.20	0.80	1.38	0.74	1.28
30	1.77	69.3	2.56	1.81	2.61	1.10	1.59	1.67	2.41	1.01	1.46	0.94	1.35
40	2.28	92.4	2.47	2.18	2.36	1.72	1.86	2.25	2.44	1.54	1.67	1.38	1.50
50	2.48	115.5	2.14	2.36	2.04	2.48	2.15	2.78	2.41	2.05	1.77	1.81	1.57
60	2.67	138.6	1.93	2.52	1.82	2.83	2.04	3.21	2.32	2.36	1.70	2.08	1.50
70	2.96	161.7	1.83	2.72	1.69	3.15	1.95	3.54	2.19	2.53	1.57	2.26	1.40
80	3.21	184.8	1.74	3.09	1.67	3.45	1.87	3.71	2.01	2.63	1.42	2.40	1.30
150	3.69	346.0	1.07	3.57	1.03	3.04	0.88	3.62	1.05	3.10	0.90	3.04	0.88
250	4.15	577.0	0.72	4.10	0.71	4.30	0.75	4.45	0.77	3.38	0.59	3.11	0.54
400	5.06	923.2	0.55	4.46	0.49	4.92	0.53	5.15	0.56	3.80	0.41	3.58	0.39
500	5.70	1154	0.50	4.80	0.42	6.12	0.53	5.77	0.50	4.30	0.37	3.94	0.34

is shown to be a straight line in Fig. 12.

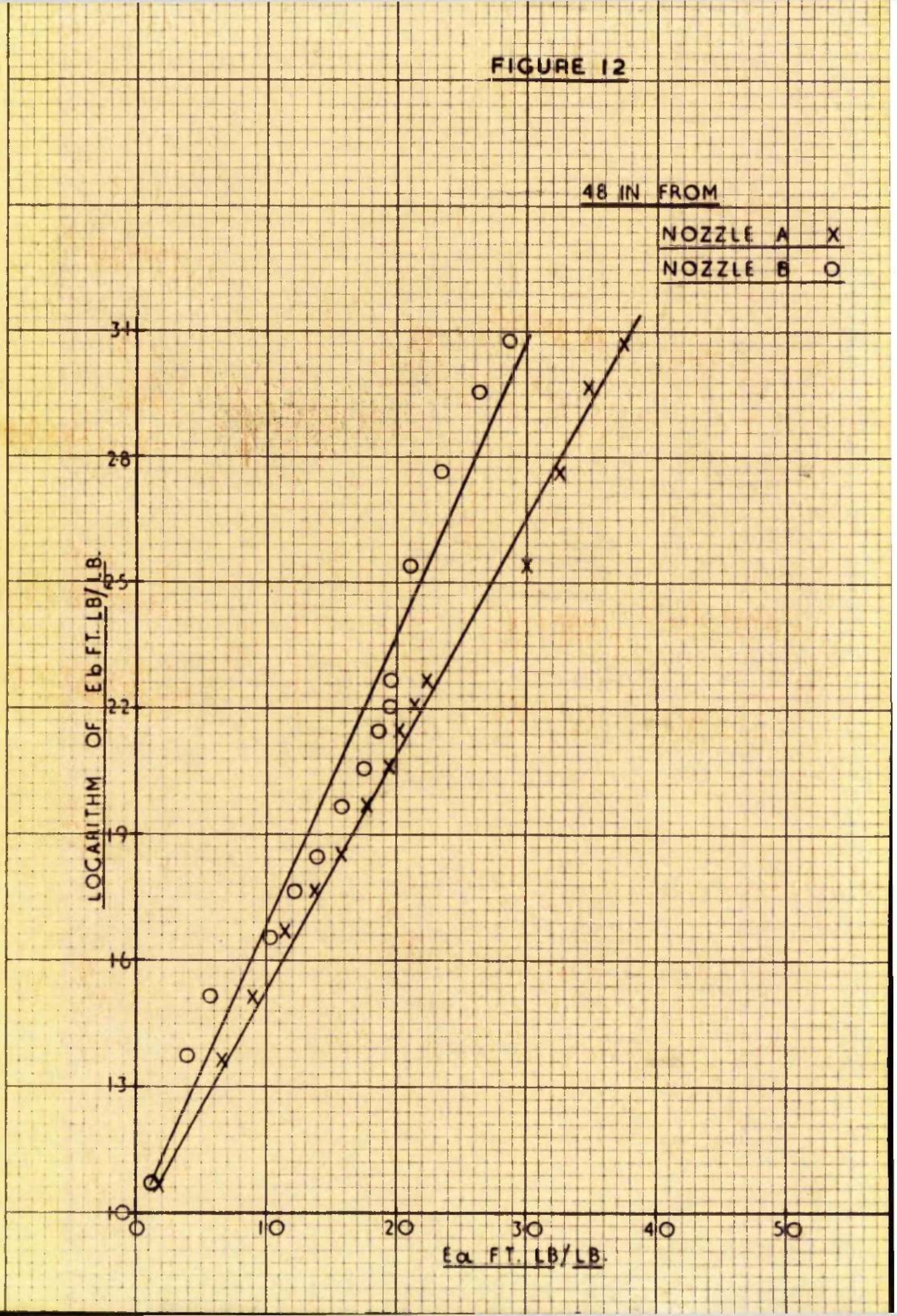
The percentage of the pressure energy actually used in atomisation or energy utilisation is also shown for each pressure in Table 9. The energy utilisation rises sharply till it reaches a maximum of about 2.5 per cent with nozzles A and B at about 30 lb./ in^2. falling off at higher pressures. This indicates that these nozzles are using the pressure energy supplied to them most efficiently at this pressure. Nozzles C, D, F and G use the energy supplied most efficiently at about 50 lb./in^2. It can be noted that as the orifice diameter of the nozzle increases and, consequently, the throughput for the same applied pressure, the efficiency of the atomising process gradually decreases. This appears to be due to more of the applied energy being utilised in propelling a greater volume of liquid through the nozzle.

It is possible to calculate the efficiency of an atomising process in one operation following a method suggested by Nugele and Evans (104). The efficiency of an atomising operation in which a fraction E of the energy lost in pressure drop Δp is used in forming new surface may be expressed by

$$E\,(\pi d^3\,\Delta p/6) = \pi d^2 \sigma \quad 6 \text{ for a single drop or}$$

$$E\,\Delta p \Sigma d^3 = 6\sigma \Sigma d^2 \quad \text{for the entire spray}$$

FIGURE 12


48 IN FROM
NOZZLE A X
NOZZLE B O
LOGARITHM OF Eb FT. LB/LB.
31
28
25
22
19
16
13
10
0
10
20
30
40
50
Ea FT. LB/LB.

where d is the droplet diameter and σ is the interfacial tension of the liquid. Results obtained by both methods compare very well as shown in Table 10 below for nozzle A at 150 lb./in^2.

Table 10.

100 Em/Ep	Using Above Formula
1.07	1.11

Variation of Spray with Distance from Nozzle

Since average droplet size and droplet size distribution vary with distance from the nozzle it was decided to investigate the variation.

From Tables 6 and 7 it can be seen that at low pressures, i.e. below about 30 lb./in^2, the average droplet size decreased with distance to 48 ins. from the nozzle. At higher pressures, however, mainly above 60 lb./in^2. the average droplet size increased with distance. This is explained by the shorter range of the smaller droplets and their predominance at higher pressures. Garner and Henry (105) came to a similar conclusion on studying the behaviour of sprays under high

altitude conditions.

In order to obtain a more exact picture of the relationship between distance from nozzle and average droplet size obtained, the spray from nozzle A at 60 lb./in.^{2} was sampled at the additional distances of 28,38 and 60 ins. from the nozzle. These results are given in Fig. 13. They show that the A.D.S. increases with increase in distance from the nozzle.

Fig. 14. shows the variation in droplet size distribution obtained for nozzle A at 60 lb./in.^{2} sampled at 8 and 60 ins. from the nozzle. This shows even more clearly how a larger droplet size is obtained at a greater distance from the nozzle.

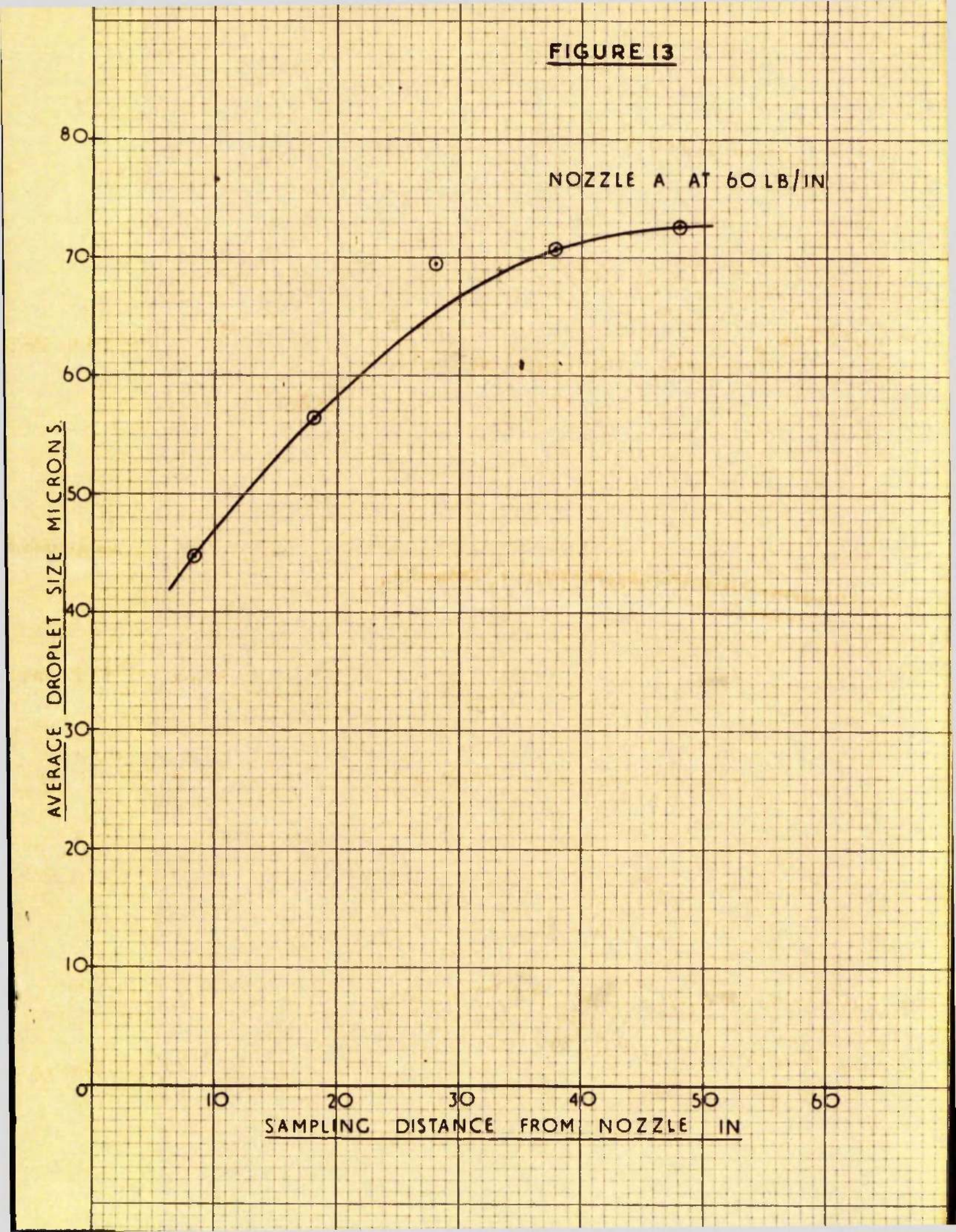
The slope of the line (n) relating A.D.S. and log P is consequently affected by this variation. The plot obtained using the data in Tables 6 and 7 is shown in Fig. 15. and the values of n obtained are shown in Table 11 below.

Table 11

Values of n

Distance from Nozzle A ins.					
8		18		48	
Below 30lb./in.^{2}	Above 30lb./in.^{2}	Below 30lb./in.^{2}	Above 30lb./in.^{2}	Below 30lb./in.^{2}	Above 30lb./in.^{2}
-0.92	-0.43	-0.98	-0.38	-1.12	-0.31

FIGURE 13


NOZZLE A AT 60 LB/IN
AVERAGE DROPLET SIZE MICRONS
0
10
20
30
40
50
60
70
80
10
20
30
40
50
60
SAMPLING DISTANCE FROM NOZZLE IN

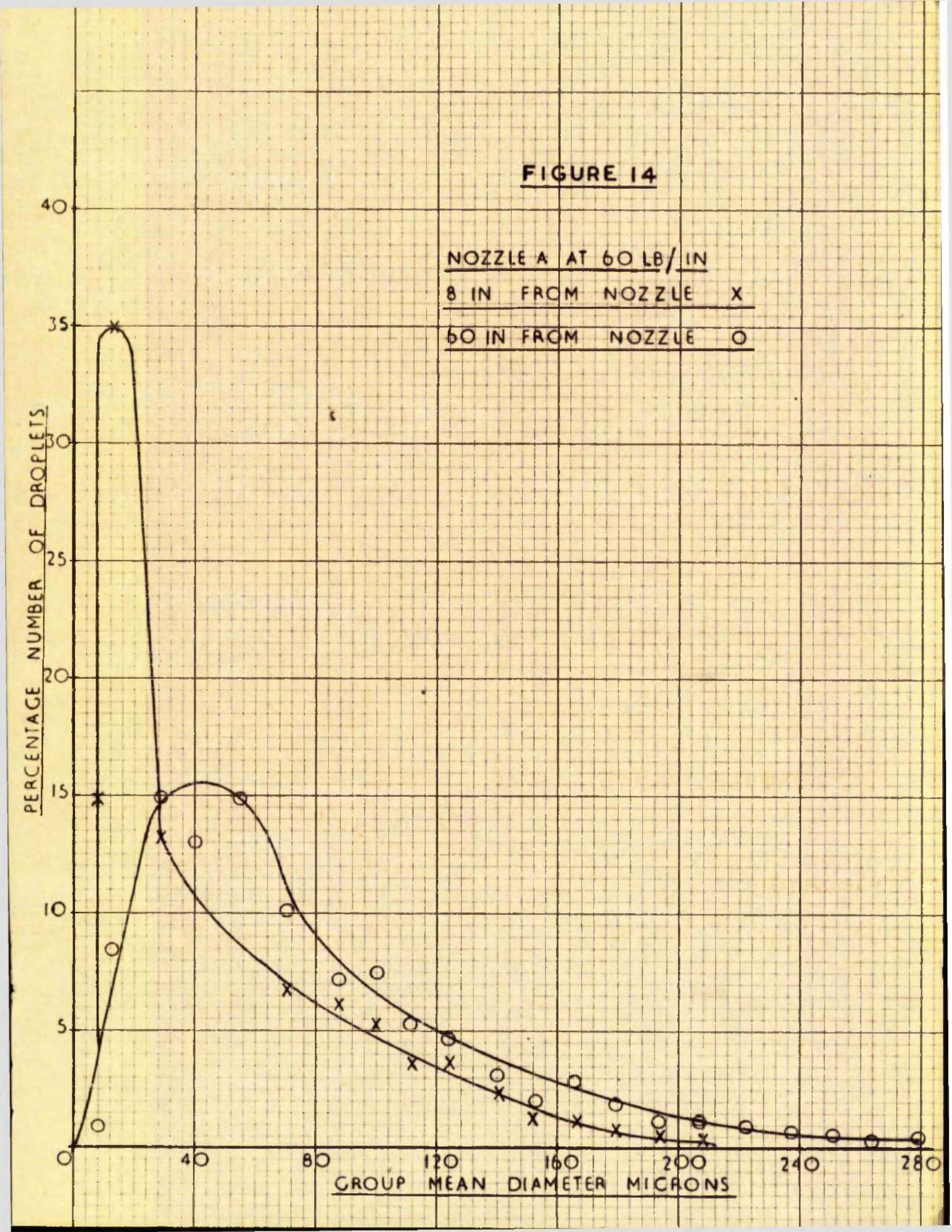
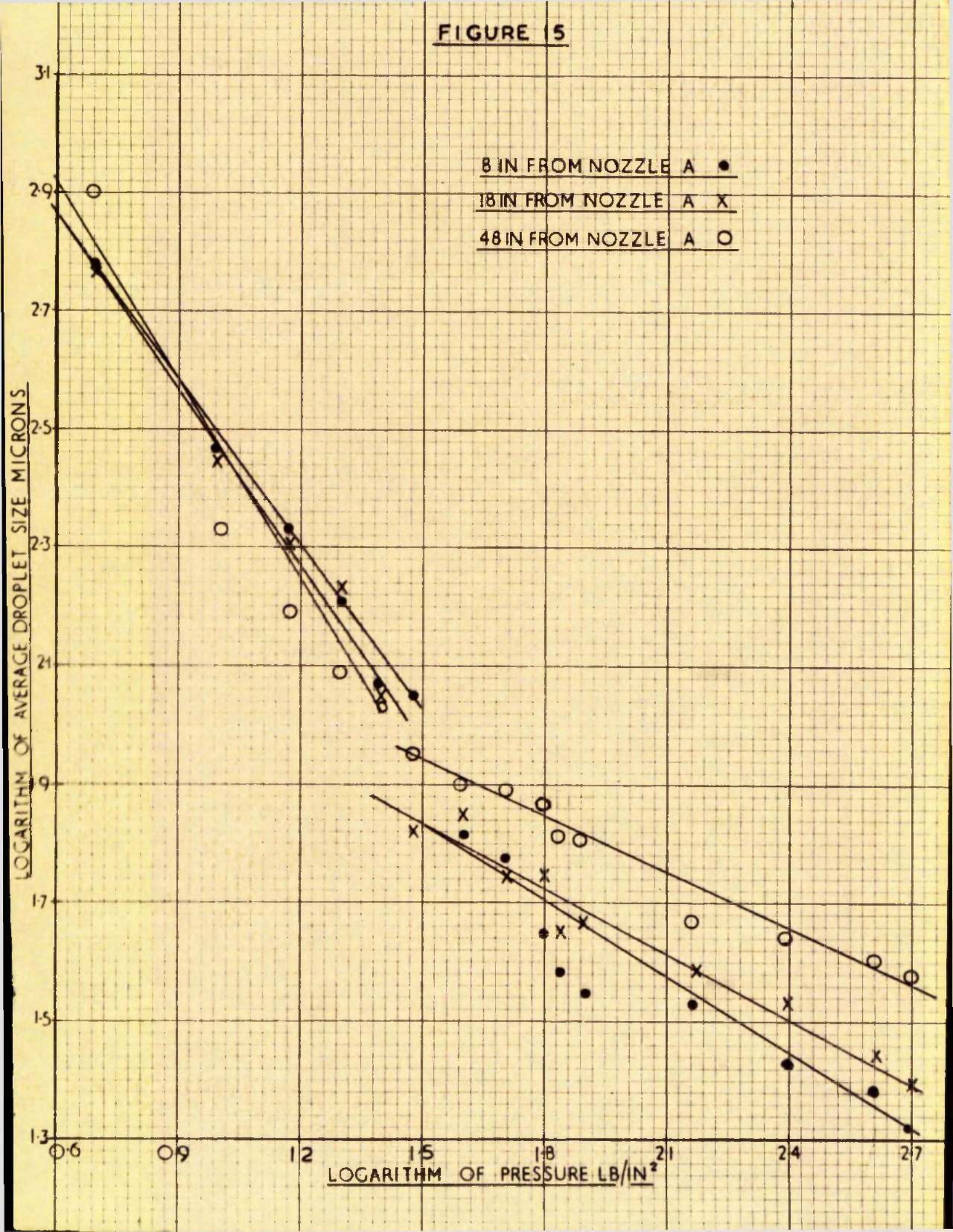


FIGURE 14
NOZZLE A AT 60 LB/IN
8 IN FROM NOZZLE X
60 IN FROM NOZZLE O
PERCENTAGE NUMBER OF DROPLETS
0
5
10
15
20
25
30
35
40
40
80
120
160
200
240
280
GROUP MEAN DIAMETER MICRONS

FIGURE 15


8 IN FROM NOZZLE A ●
18 IN FROM NOZZLE A X
48 IN FROM NOZZLE A O
LOGARITHM OF AVERAGE DROPLET SIZE MICRONS
3·1
2·9
2·7
2·5
2·3
2·1
1·9
1·7
1·5
1·3
0·6
0·9
1·2
1·5
1·8
2·1
2·4
2·7
LOGARITHM OF PRESSURE LB/IN²

The variation in A.D.S. with distance shows in the values of n obtained, the higher values of A.D.S. obtained with distance from the nozzle showing in decreased slope. This decrease is also apparent in the values obtained below about 30lb./in^2.

SECTION 2

Effect of Surface Tension on Droplet Size

Liquid surface tension and viscosity forces in general oppose the disintegration of a liquid jet. According to Hinze (71) the action of the surface tension forces is twofold, hindering the first development of surface distortions into ligaments and aiding the final stages of disruption. Therefore, whether the formation of ligaments assumed by Castleman (55) takes place as an intermediate step between the continuous jet and the separate droplets, or whether, on the other hand, it is assumed that droplets are directly formed after breaking off from the fringe of the liquid cone, surface tension is obviously an important factor (Klusener (72) and Littaye (73)). During the third and final stage of atomisation when the droplets already formed are further split up by the surrounding medium, the surface tension forces will again play an important part.

The surface tension of the atomised liquid is of course also important in influencing the ease with which the droplet wets a dust particle. A low liquid / solid interfacial tension allows the liquid to spread out and wet the solid. The interfacial tension between water and certain dusts, e.g. coal dust, is relatively high and as a result it is only with great difficulty that these dusts are wetted. It is,

therefore, recognised that the use of a low surface tension liquid should be of assistance in allaying dust.

In an earlier study of atomisation by the swirl atomiser (106) it has been shown that while the use of solutions of surface-active agents in place of water results in improved atomisation at low values of applied pressure, at the higher pressures, such as are used industrially to suppress dust, the gain was negligible. The surface-active materials tested were all powerful commercial wetting agents which would be expected to have a very high rate of adsorption at the water/air interface. Moreover, owing to the relatively large molecules involved, adsorption could hardly be expected to be easily and completely reversible (107). It had been thought, therefore, that the equilibrium surface tension of these solutions would be achieved almost simultaneously with the formation of a spray droplet. In spite of this the droplets produced from such solutions were much larger at high atomising pressures than could be predicted by comparing their equilibrium surface tension ("static" value) with that of water. It seemed that even with such surface active agents the formation of new surfaces by atomisation at high pressures was too rapid for adsorption to complete itself in the time available and some intermediate ("dynamic") value of surface tension typical of

a freshly formed surface was effective. With the low concentrations of surface-active agents used this dynamic value would approach the equilibrium value for pure water.

It was now proposed to test this theory and extend our knowledge of the effect of surface tension on atomisation by atomising a variety of liquids. These were as follows :

(a) Liquids of constant surface tension and of viscosity approximating to that of water. Those chosen were :

cycloHexane

Carbon tetrachloride

A mixture of Kerosene and 60/80 Petroleum Ether (hereafter referred to as K - PE)

(b) Aqueous solutions of weak surface-active agents, e.g.

isoButyl alcohol

isoAmyl alcohol

sec.-Octyl alcohol

(c) Aqueous solutions of strong surface-active agents, e.g.

Sodium oleate

Sodium laurate

(d) Aqueous solutions of inorganic salts of equilibrium surface tension higher than that of water, e.g.

Sodium chloride

Calcium chloride

Magnesium chloride

The alcohols used were laboratory reagent grades. The sodium laurate obtained in technical form was purified by recrystallisation from methyl alcohol, washing with ether, and drying in a vacuum oven. The sodium oleate was prepared from pure oleic acid by neutralising with caustic soda, both being in alcoholic solution. Phenolphthalein was used as external indicator. The sodium salt was isolated by evaporation. It was recrystallised from alcohol, filtered, washed with a little ether, dried in a vacuum oven and kept in a vacuum desiccator.

Spray Apparatus and Droplet Sampling Method

The low pressure spray with nozzle A as described in Section 1, page 23 , was employed here, and since the A.D.S. and size distribution of the spray were found to alter with distance sampling was carried out at 18 ins. from the nozzle in all cases. The droplet sampling method employed in Section 1 was found satisfactory for the aqueous sprays. cycloHexane, carbon tetrachloride and K-PE sprays could not, however, be sampled in this way as they were soluble in kerosene. Other immersion liquids were tried with little success, none being of sufficiently low density to allow the droplets to sink and prevent their evaporation. It was therefore decided to use an 'impressions method' of measuring droplet

size. In this method the target, usually a microscope slide, is covered with a suitable coating which must be of fine-grain structure so that even the smallest droplet impressions are distinct. May (108) used a coating of magnesium oxide obtained by burning a magnesium ribbon and he related the size of the impressions formed to the droplet size. By this method droplets down to 5 microns can be detected at sufficiently high impact velocities. Strashevsky (109) used a layer of carbon deposited from a smoky flame to detect droplets. The magnesium oxide impression method was found very satisfactory for sampling cyclohexane, carbon tetrachloride and K-PE. Droplets of these liquids were sampled by this method.

Kerosene + Pet. Ether.

Slide Preparation

The magnesium oxide layer was prepared by moving a burning magnesium ribbon to and fro under a microscope slide at a distance such that the tip of the flame just cleared the glass. A five inch length of one eighth ribbon gave a layer of adequate thickness. The oxide which adhered to the glass was smooth and soft with a grain size of about 0.5 microns.

A droplet striking such a surface penetrates and leaves a well defined circular impression which can be viewed by strong transmitted light under a microscope. The

impressions appear as bright spots on a darker background. The layer should be as thick as the diameter of the droplet and preferably about twice as thick. However, if the layer is too thick it is inconveniently fragile and flakes off the slide easily.

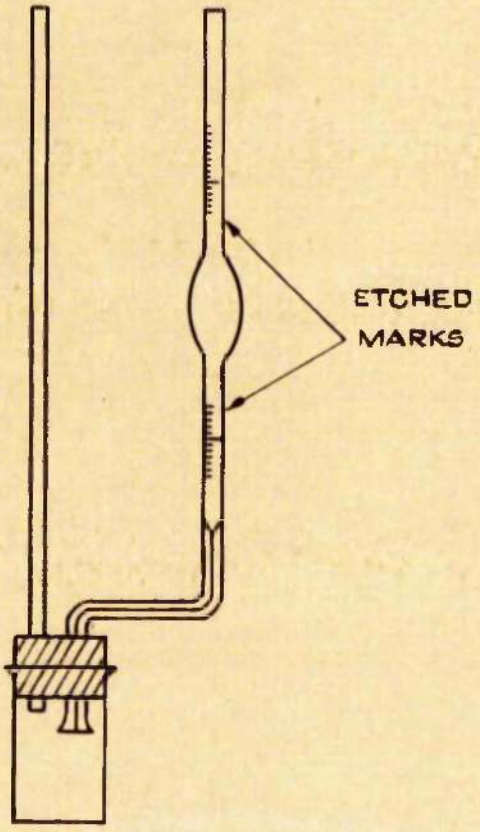
Measurement of Surface Tension

A drop method of measuring surface tension was employed using Traube's stalagmometer. The dropping-tube consisted of a capillary tube, one end of which was flattened out to give a large dropping surface which was carefully ground flat and polished. The capillary was sealed on to a tube of wider bore on which a bulb was blown and on the stem of the tube two marks were etched, one above and one below as shown in Fig. 16.

The surface tension was calculated from the number of drops of liquid which fell from the end of the stalagmometer while the level of the liquid was falling from the upper to the lower etched mark. To increase the accuracy of the readings, the tube above and below the bulb was marked with a scale. With the aid of the additional marks, fractions of a drop could be estimated, to an accuracy of 0.05 of a drop. To ensure that only the equilibrium value of surface tension was measured the velocity of the liquid flow had to be regulated so that the

FIGURE 16.

TRAUBE'S STALAGMOMETER.



number of drops per minute did not exceed fifteen.

The ratio of the surface tensions of the two liquids is given by the expression

$$\gamma_1 / \gamma_2 = n_2 d_1 / n_1 d_2$$

where n_1 and n_2 are the numbers of drops yielded by the same volume of liquid and d_1 and d_2 are the liquid densities. To enable constant temperature to be maintained throughout the determinations, the end of the stalagmometer was passed through a rubber stopper which fitted into the neck of a small bottle and the whole apparatus placed in a thermostat. The estimations were repeated until the number of droplets obtained for each liquid did not vary by more than 0.3 to 0.5 of a drop. Distilled water was used as the comparison liquid. In order to ensure maximum accuracy, no glass or liquid surfaces were left exposed to the air and the working surfaces were cleaned between each measurement, the cleaning sequence being chromic acid, distilled water, alcohol and ether.

Results

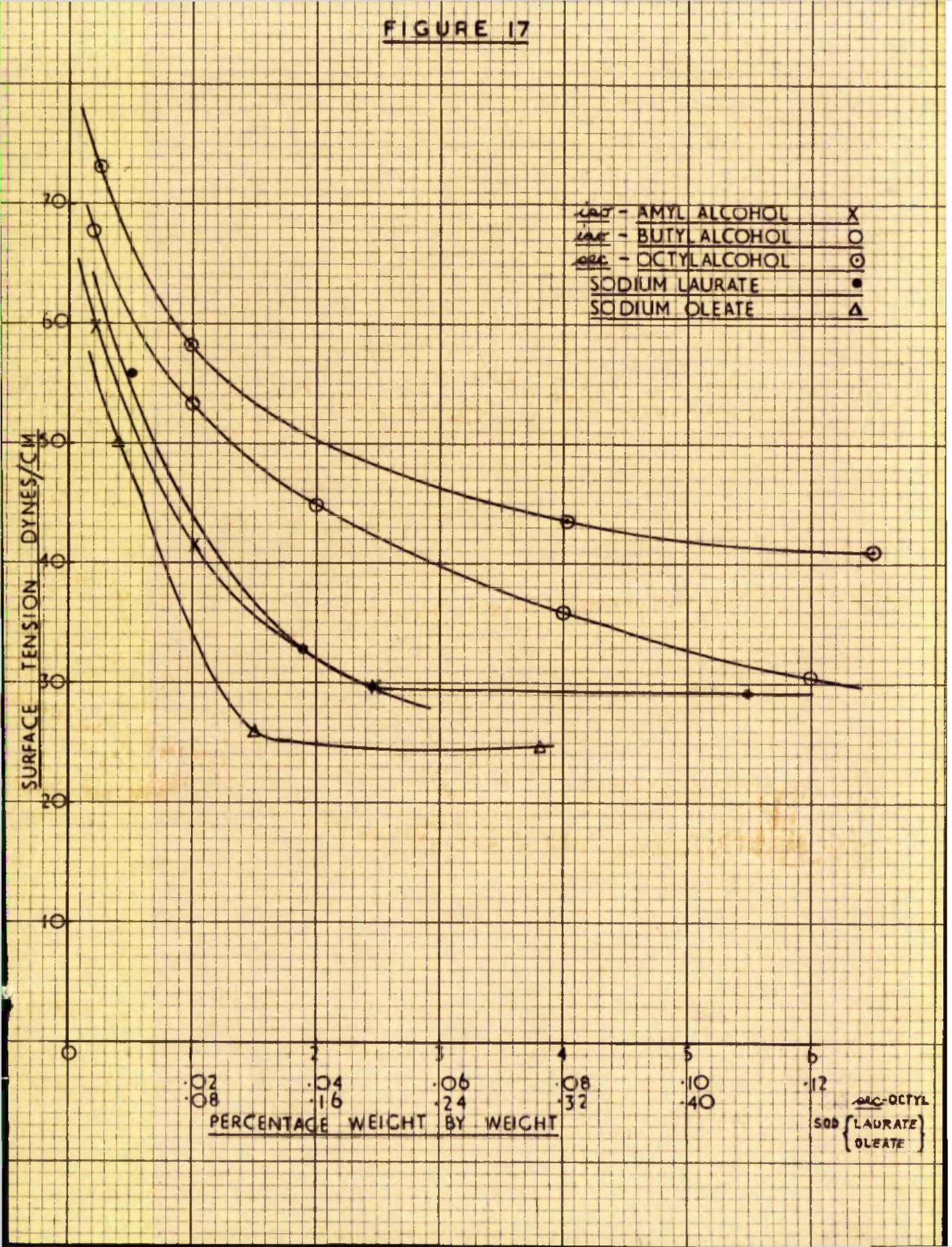
The surface tensions and viscosities of the liquids of group (a) are given in Table 12. The viscosities were obtained at 20° with a standard U - tube viscometer.

Table 12

Liquid	Viscosity at 20° C dyne sec/cm^2 x 10^{-2}	Surface Tension at 20° C dynes/cm.
Water	1.01	72.5
cycloHexane	1.03	25.1
Carbon tetrachloride	0.96	26.9
K-PE	1.04	23.5

The variation of surface tension with solution concentration, as determined by means of Traube's stalagmometer for aqueous solutions of soaps and alcohols are shown in Fig. 17. From this the concentrations necessary to give solutions of surface tensions 33 and 56 dynes/cm of the materials in groups (b) and (c) were noted and such solutions prepared. Solutions of sodium laurate and sodium oleate of surface tension 29 dynes/cm. were also prepared. Using the concentrations given in the "Handbook of Physics and Chemistry "(1954 edition), solutions of the materials in group (d) were prepared of surface tension 82.5 dynes/cm. An additional solution of calcium chloride of surface tension 90.4 dynes/cm.

FIGURE 17


AMYL ALCOHOL X
BUTYL ALCOHOL O
OCTYL ALCOHOL ⊙
SODIUM LAURATE •
SODIUM OLEATE Δ
SURFACE TENSION DYNES/CM
70
60
50
40
30
20
10
0
1
2
3
4
5
6
·02
·04
·06
·08
·10
·12
·08
·16
·24
·32
·40
PERCENTAGE WEIGHT BY WEIGHT
OCTYL
SOD {LAURATE OLEATE}

further extended the range of surface tension investigated. The materials used were A.R. quality salts.

Comparison of Sampling Methods

Water droplets sprayed from nozzle A at pressures varying from 10 - 60 lb./in^2. were sampled both by the immersion liquid method using Kerosene - Vaseline and by the impressions method using magnesium oxide. The average droplet size was calculated in each case and the results plotted in Fig. 18.

It can be seen that the same straight line can be drawn through both sets of points indicating that results obtained using the impressions method can be directly compared with those using the immersion liquid technique.

Effect of Pressure on Droplet Size

The liquids of group (a) were atomised in turn in the apparatus shown in Fig. 3 (Section 1.) over a range of pressure. The average droplet sizes calculated are given in Table 13.

It can be seen that as before the average droplet size decreased with increase in pressure. At low pressures, however, the average droplet size obtained at constant pressure decreases as surface tension decreases. The surface tension effect becomes less apparent as pressure increases until at about 60 lb./in^2. all the liquids tested gave the same degree of

FIGURE 18

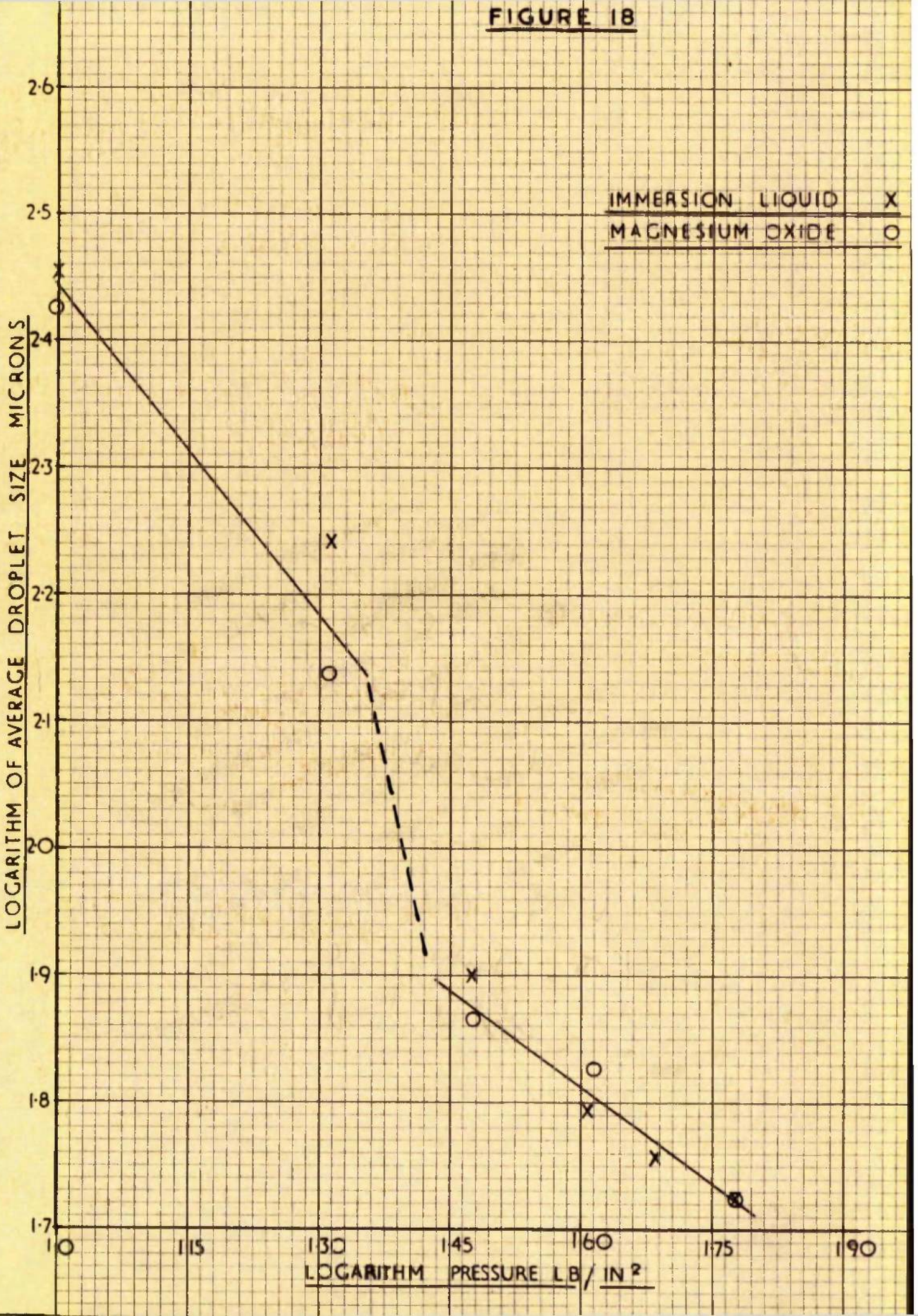

IMMERSION LIQUID X
MAGNESIUM OXIDE O
LOGARITHM OF AVERAGE DROPLET SIZE MICRONS
2·6
2·5
2·4
2·3
2·2
2·1
2·0
1·9
1·8
1·7
1·10
1·15
1·30
1·45
1·60
1·75
1·90
LOGARITHM PRESSURE LB/IN²

Table 13

	Average Droplet Size (Microns)					
Pressure lb./in.^{2}	10	20	30	40	50	60
Water	268	138	73.5	66.7	56.3	53
Carbon tetrachloride	214	83.5	70.4	56.9	-	50.5
cycloHexane	157	88.1	70.6	56.6	51.2	49.1
K-PE	157	95.9	85.4	71.1	61.0	58.3

atomisation as water. The aqueous solutions were atomised in the same way and over the same range of pressure. The average droplet sizes are given in Table 14. Again it can be seen that at 60lb./in^2. the surface tension appears to have little effect, the degree of atomisation obtained being similar to that of water.

As no improvement in atomisation was achieved by using liquids of low surface tension above 60lb./in^2., and the pressure range of 0 - 80lb./in^2. is of most interest in dust suppression work, compressed air supply in mines usually being 60lb./in^2., only sodium laurate solution of surface tenison 33 dynes/cm. was atomised over the range 0 - 500 lb./in^2. The results are tabulated in Table 15 and show little variation from the values obtained for water particularly above 30 lb./in^2.

Energy Utilisation

If the actual energy used in the atomisation process (Ea ; ft.lb./lb.) is considered there is a difference between the values obtained for water and those for the other liquids (Table 14.) This is also shown in the percentage pressure energy (Ep) utilised in the atomisation process also tabulated for each value of applied pressure. Less energy appears to be required

Table 14

Surface tension dynes/cm.	29						33											
S/A agent	Sodium Laurate			Sodium Oleate			Sodium Laurate			Sodium Oleate			Iso-Amyl Alcohol			Iso-Butyl Alcohol		
Press. lb/in^2.	ADS micron	Ea ft.lb/lb	100Ea Ep	ADS micron	Ea ft.lb/lb	100Ea Ep	ADS micron	Ea ft.lb/lb	100Ea Ep	ADS micron	Ea ft.lb/lb	100Ea Ep	ADS micron	Ea ft.lb/lb	100Ea Ep	ADS micron	Ea ft.lb/lb	100Ea Ep
10	198	0.29	1.25	195	0.29	1.25	210	0.31	1.34	210	0.31	1.34	195	0.34	1.47	205	0.32	1.38
20	131	0.44	0.95	130	0.44	0.95	139	0.51	1.10	142	0.47	1.02	137	0.48	1.04	134	0.49	1.06
30	89.5	0.72	1.04	72.4	0.80	1.16	82.8	0.80	1.16	78.5	0.84	1.21	82.8	0.80	1.16	81.4	0.81	1.17
40	66.1	0.88	0.95	-	-	-	64.8	1.02	1.10	-	-	-	-	-	-	-	-	-
50	66.4	0.89	0.77	-	-	-	60.6	1.09	0.95	-	-	-	-	-	-	-	-	-
60	58.2	1.0	0.72	58.3	1.0	0.72	54.7	1.21	0.87	54	1.22	0.88	59.2	1.12	0.81	54	1.22	0.88

Surface tension dynes/cm.	56															72.5		
S/A agent	Sodium Laurate			Sodium Oleate			Iso-Amyl Alcohol			Iso-Butyl Alcohol			Iso-Octyl Alcohol			Water		
Press. lb/in^2.	ADS micron	Ea ft.lb/lb	100Ea Ep	ADS micron	Ea ft.lb/lb	100Ea Ep	ADS micron	Ea ft.lb/lb	100Ea Ep	ADS micron	Ea ft.lb/lb	100Ea Ep	ADS micron	Ea ft.lb/lb	100Ea Ep	ADS micron	Ea ftlb/lb	100Ea Ep
10	276	0.41	1.78	208	0.56	2.34	194	0.58	2.51	222	0.51	2.2	202	0.55	2.38	268		
20	139	0.80	1.73	143	0.78	1.69	124.5	0.90	1.95	139	0.81	1.75	125	0.82	1.78	138		
30	77	1.46	2.11	78	1.43	2.06	83.2	1.35	1.95	78.5	1.43	2.06	79	1.42	2.05	73.5		
40	-	-	-	64.5	1.74	1.88	-	-	-	-	-	-	-	-	-	66.7		
50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	56.3		
60	55.1	2.03	1.47	54.5	2.06	1.49	58.1	1.93	1.39	57.1	57.1	1.42	57.3	1.96	1.42	53.0		

Surface tension dynes/cm.	82.5						90.4								
Salt Solution	Sodium Chloride			Magnesium Chloride			Calcium Chloride			Calcium Chloride					
Viscosity $\times 10^2$ dyne sec/cm	2.22			3.71			2.66			4.69					
Press. lb/in^2.	ADS micron	Ea ft.lb/lb	100Ea Ep	ADS micron	Ea ft.lb/lb	100Ea Ep	ADS micron	Ea ft.lb/lb	100Ea Ep	ADS micron	Ea ft.lb/lb	100Ea Ep	ADS micron		
10	298	0.56	2.4	459	0.36	1.56	327	0.51	2.18	467	0.39	1.69			
20	179	0.92	1.99	195	0.85	1.84	192	0.86	1.87	251	0.72	1.56			
30	90.5	1.82	2.63	140	1.18	1.70	128	1.29	1.86	156	1.16	1.68			
40	84.2	-	-	92.5	1.79	1.94	72	2.43	2.49	120	1.50	1.62			
50	66.1	-	-	84	1.97	1.71	57	2.9	2.51	97.5	3.14	2.72			
60	53.5	3.09	2.23	63.6	2.99	1.87	52	3.17	2.29	51.2	3.52	2.54			
70	-	-	-	49.1	3.36	2.08	-	-	-	-	-	-			
80	-	-	-	41.8	3.94	2.13	-	-	-	-	-	-			

to effect atomisation if the liquid has a low surface tension, especially at high pressures. This is more easily seen in graphical form as in Fig. 19. which is a plot of pressure energy supplied (Ep) to the energy required for atomisation for water and sodium laurate solution of surface tension 33 dynes/cm. from 0 to 500 lb./in^2. It is of interest to note that a drop in surface tension from 72.5 dynes/cm. to 33 dynes/cm. is not accompanied by a large enough decrease in droplet size to maintain the values of Ea found for water. Above 80 lb./in^2. the change in droplet size is so slight that the following relation holds approximately

$$Ea_1 / Ea_2 = \gamma_1/\gamma_2$$

as shown in Table 15, the subscript 1 referring to water and 2 to the other liquid.

A lowering of surface tension, therefore, improves atomisation though it appears to be much less than would have been expected from the values of static or equilibrium surface tension, as less of the available energy (Ep) is utilised in the process. If, for example, the solution of sodium laurate of surface tension 33 dynes/cm is under an applied pressure of 40 lb./in^2. and has the same value of Ea as water at that pressure

FIGURE 19.

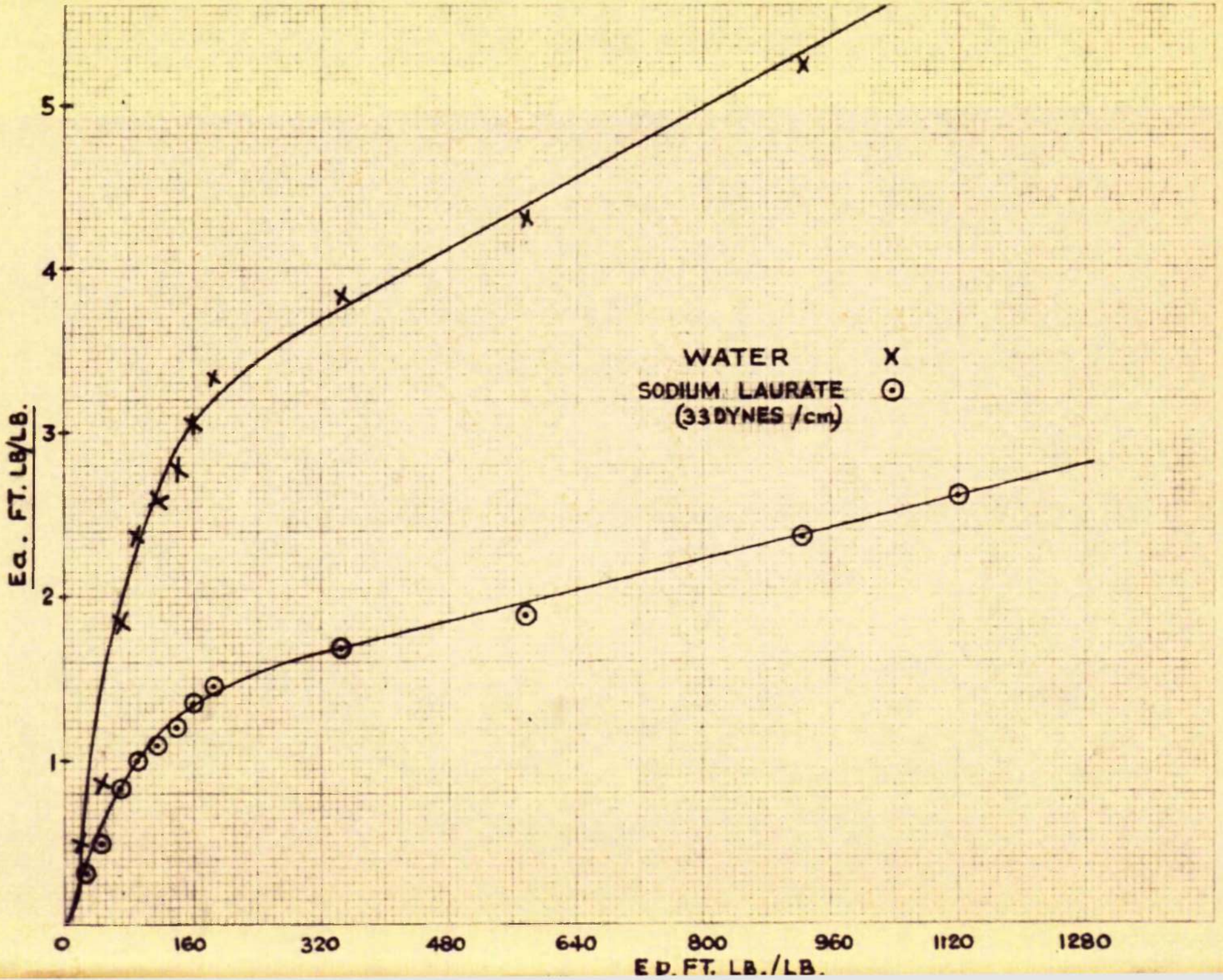

WATER X
SODIUM LAURATE ⊙
(33 DYNES /cm)
Eq. FT. LB/LB.
5
4
3
2
1
0
160
320
480
640
800
960
1120
1280
E D. FT. LB./LB.

Table 15

= 2.23

	Sodium Laurate = 33 dynes/cm.				Water = 73.5 dynes/cm.	
Pressure lb./in^2.	Ep ft.lb/lb	A.D.S.	En ft.lb/lb	$\frac{En_1}{En_2}$	A.D.S.	En ft.lb/lb
10	23.1	210	0.31	1.68	284	0.52
20	46.2	130	0.51	1.67	174	0.85
30	69.3	82.8	0.80	2.30	80	1.84
40	92.4	64.8	1.02	2.33	62	2.38
50	115.5	60.6	1.09	2.37	57	2.58
60	138.6	54.7	1.21	2.30	53	2.78
70	161.7	48.3	1.37	2.25	48	3.07
80	184.8	45.1	1.46	2.29	44	3.34
150	346	39.0	1.69	2.27	38.4	3.84
250	577	34.9	1.89	2.27	34.2	4.30
400	923.2	27.9	2.37	2.21	28.1	5.24
500	1154	25.2	2.62	2.26	24.9	5.91

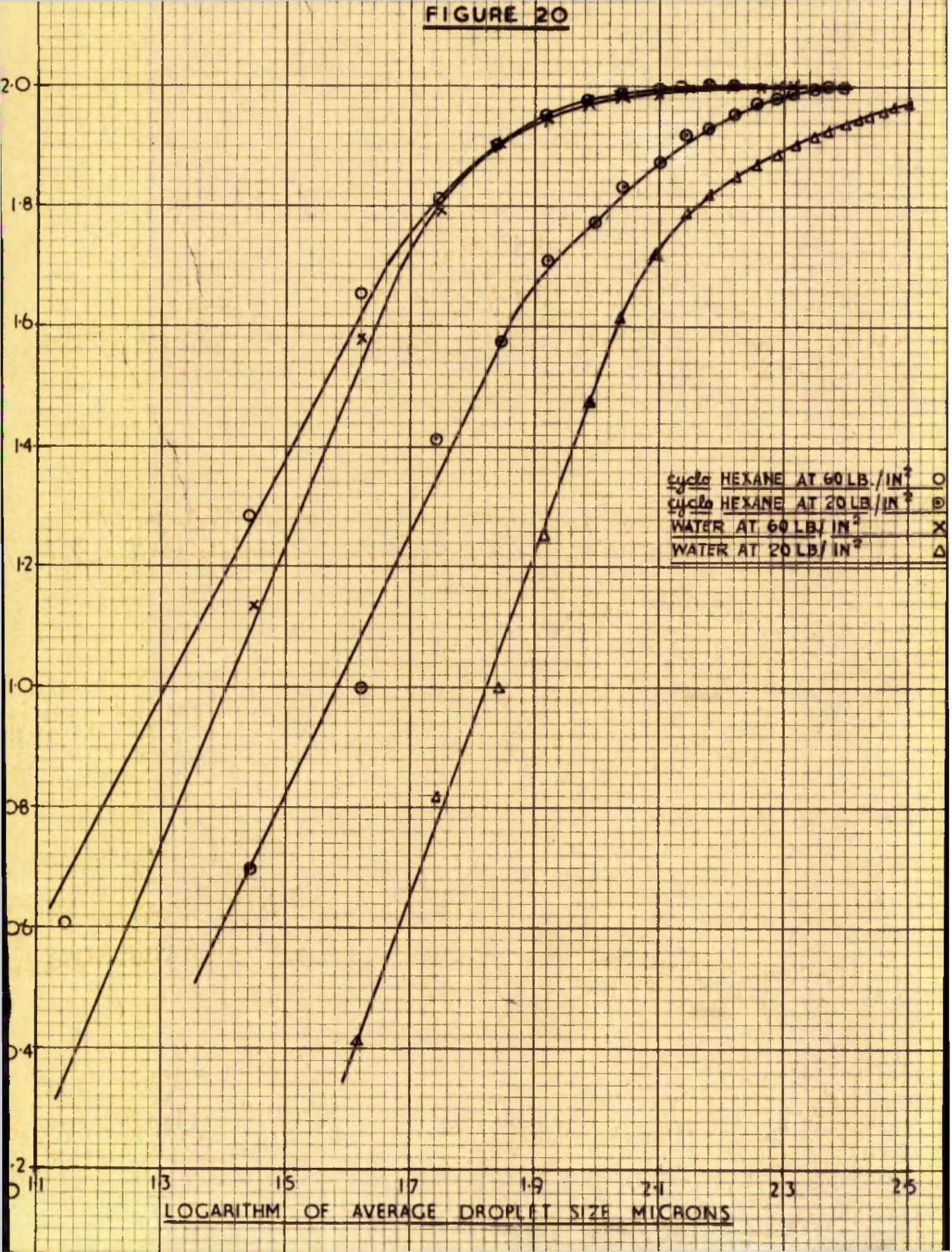
(i.e. 2.2 ft.lb./lb.), the average droplet size obtained should be 30 microns whereas it was actually 65 microns. As already stated the surface tension values quoted are static values at equilibrium adsorption for the solutions tested. As the atomising pressure is increased the time interval for the formation of a droplet is small and becomes comparable with the time of adsorption to equilibrium, i.e. the time of change from dynamic to static surface tension. The dynamic surface tension of 0.02 percent sec-octyl alcohol quoted by Posner and Alexander (110) is 72 dynes/cm. at 0.001 sec. and falls to a steady value of 56 dynes/cm. after 0.02 sec. which is the value of static surface tension for that concentration of sec-octyl alcohol.

Addison and Elliot (106) working on the dynamic surface tensions of solutions of ethyl alcohol, iso-amyl and sec-octyl alcohols, found that the surface tension at the moment of issue from the orifice was approximately that of pure water. We therefore have a range of surface tension even at zero time from the low values of pure liquids like carbon tetrachloride, to the high values of the aqueous solutions and water. It would therefore appear that at a pressure of about 60 lb./in^2.

the average droplet size produced is independent of the surface tension of the liquid no matter whether the dynamic or static value is considered. At high pressure the force of atomisation is relatively so much greater than the surface energy forces that the latter play a very small part in the proceedings. It is assumed that all the liquids tested had similar viscosities. In fact, as can be seen from Table 1½, the viscosities of the inorganic salt solutions were at least twice that of the water but even that seemed to have little effect on the result.

It is of interest to note that different solutions at the same value of surface tension produce similar size distribution. This is shown in Fig. 20. in the form of cumulative size distribution curves at 20 and 60 lb./in^2. for cycloHexane and water. Similar curves were obtained for the other solutions. The change to the cumulative size distribution curve was made to allow the results to be presented clearly. At low pressures, 20 lb./in^2. and below, the range of droplet size and the variation obtained gives a very indefinite curve when plotted as a normal size distribution curve. These curves show that at low atomising pressures, surface tension has an influence on the distribution but at

FIGURE 20


2·0
1·8
1·6
1·4
1·2
1·0
·8
·6
·4
·2
0
1·1
1·3
1·5
1·7
1·9
2·1
2·3
2·5
LOGARITHM OF AVERAGE DROPLET SIZE MICRONS
cyclo HEXANE AT 60 LB./IN.² O
cyclo HEXANE AT 20 LB./IN.² ⊙
WATER AT 60 LB./IN.² X
WATER AT 20 LB./IN.² Δ

higher pressures it has no effect.

Effect of Concentration of Surface Active Agent

From Table 14 it is apparent that in so far as concentration of surface active agent affects the surface tension of the solution, change in concentration affect atomisation at low pressures. At higher pressures concentration of surface active agent can only affect atomisation through viscosity or density increases. It would therefore seem that gains claimed in using surface active agent solutions to lay dust (43) relate to the increased ability to wet the dust and not to improved atomisation.

SECTION 3

Effect of Sprays on Dust in Suspension

Dust Chamber

The dust sedimentation chamber employed in this study of dust suppression by aqueous sprays was cylindrical in shape, five feet in height, 18 inches in diameter, of capacity 250,964 c.c. This chamber design had certain advantages :

(a) The wall effects on the dust in suspension were made negligible by the large diameter.

(b) The cylindrical shape eliminated the 'dead' space associated with a cubic chamber of similar capacity.

(c) A thermal precipitator sample of the dust in the chamber could be taken without causing a serious decrease in the dust concentration.

(d) The diameter of the chamber enabled sprays of wide cone angles to be used with minimum loss of efficiency due to droplets striking the walls of the chamber.

Chamber Construction

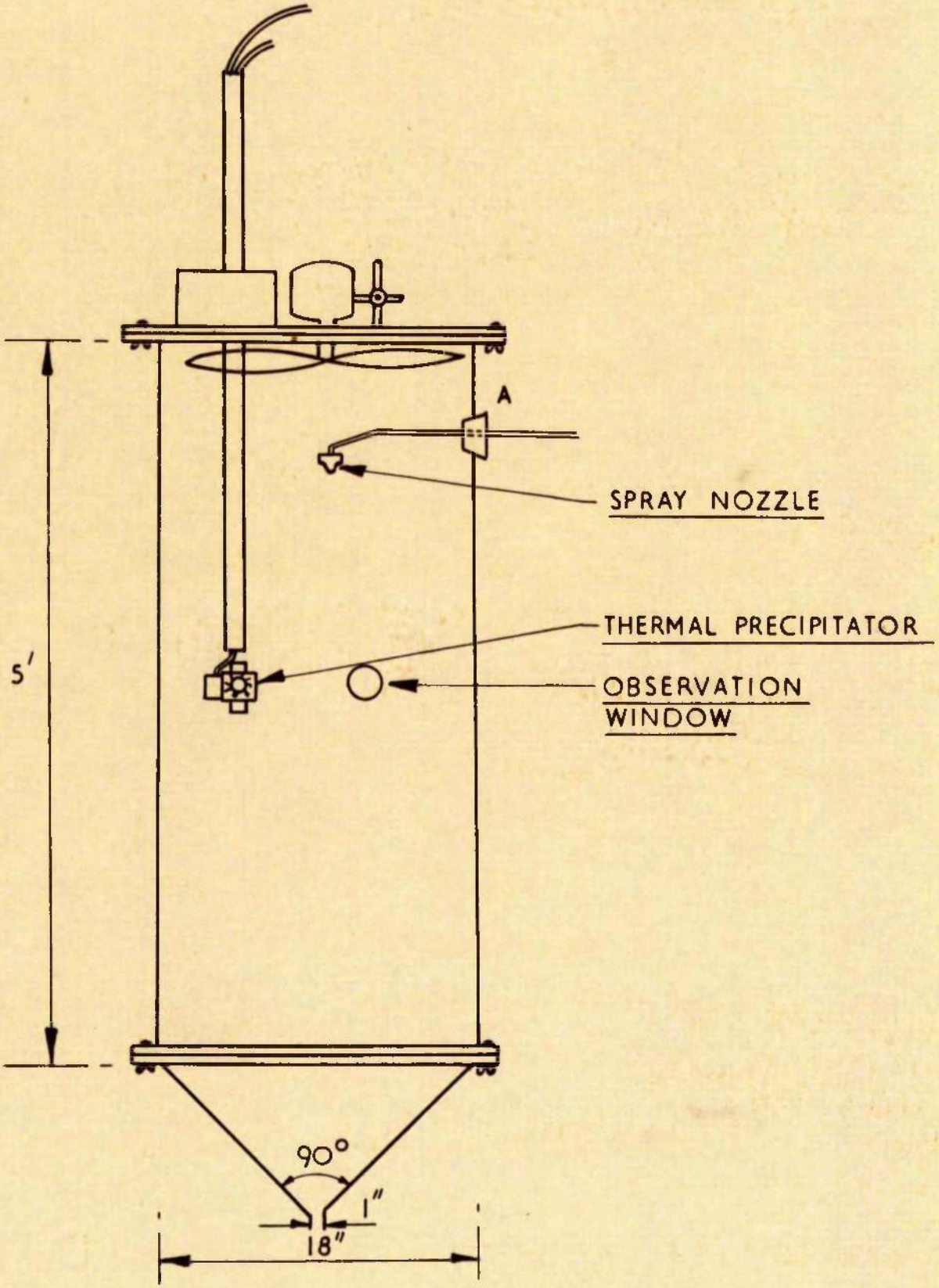
The chamber was constructed of galvanised iron coated internally with matt black paint. The conical base to assist drainage and the circular cover at the top were fitted with rubber gaskets and were held in position by eight bolts and winged nuts. A four-bladed fan, 15 inches

in width, was made from aluminium sheet and fitted through an aperture in the cover. Care was taken to hang the chamber truly vertical before it was bolted into position on the frame. A small observation window was provided to permit inspection of the dust cloud and spray. The spray nozzle could be inserted through opening A (Fig. 21) so that it would be situated at the centre of the chamber in position to spray vertically downwards. A drawing of the chamber is shown in Fig. 21.

Thermal Precipitator Unit

To enable dust samples to be taken at any level in the chamber, the Thermal Precipitator (hereafter referred to as T.P.) had to be raised and lowered inside the chamber. This was done by threading the electrical cable and aspirator connection from the T.P. head through a five foot length of one inch bore copper tubing which could be clamped in position at any height. To prevent leakage of dust from the chamber the tubing passed through a housing located on the chamber cover. This compartment was fitted with a sliding door shutting on to a rubber gasket. A sheet of blackened aluminium held against the chamber cover by a rubber gasket sealed off the chamber when the T.P. was withdrawn into the housing. The T.P. unit is a piece of standard equipment

FIGURE 21


A
SPRAY NOZZLE
THERMAL PRECIPITATOR
OBSERVATION WINDOW
5'
90°
1"
18"

and is operated in the manner recommended by Casella (111).

The apparatus employed for the production of a fine dust cloud is shown in Fig. 22. It was a modified form of that used by Dautrebande et al.(112). Air from a low pressure air blower entered the dust container through three small bore glass tubes, creating a vortex which lifted the dust up through the elutriation chamber and cyclone separator into the dust chamber. The dust cloud concentration obtained could be altered by varying the blowing period.

Only very small dust particles reached the chamber and reproducible clouds of particle size 99 per cent 5 microns were obtained which would remain in suspension long enough for measurements to be made.

The size analysis of two clouds of each of the three dusts used after one hour natural sedimentation in the chamber are given in Table 16. They show the reproducibility of the clouds with regard to particle size. Particle counts were made on the slides used for size analysis and show the reproducibility with regard to concentration, (Table 17). The size analysis of the artificial dust clouds agree very well with those for the two airborne coal dust clouds and a mixed rock and coal dust cloud sampled underground.

The reproducibility obtained with the apparatus allowed

FIGURE 22

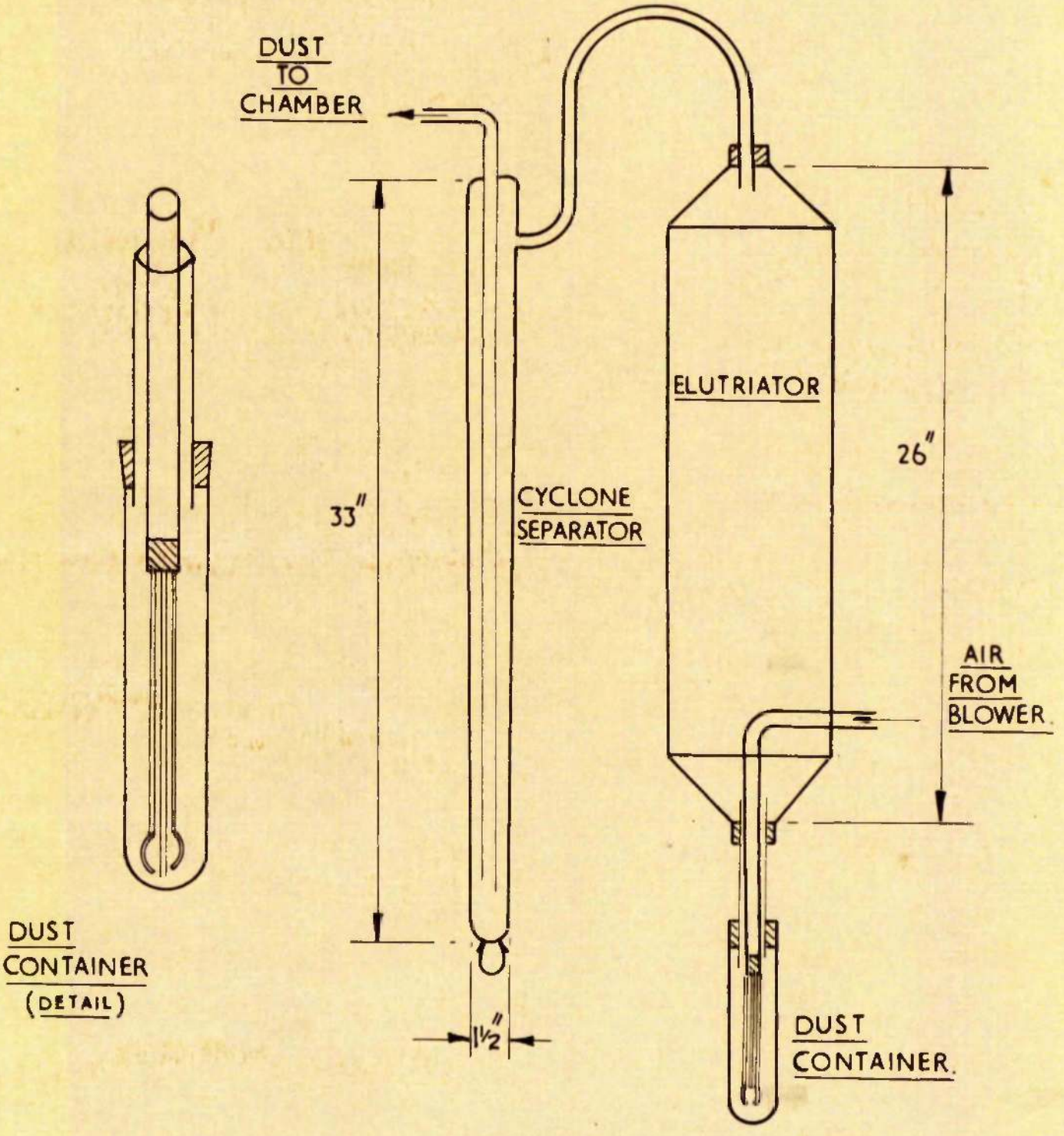

DUST
TO
CHAMBER
ELUTRIATOR
26"
33"
CYCLONE
SEPARATOR
AIR
FROM
BLOWER
DUST
CONTAINER
(DETAIL)
1½"
DUST
CONTAINER.

TABLE 16

Percentage Number of Particles

Size Microns	Coal Dust		Silica Dust		Fly Ash		Natural Airborne Coal Dust		Mixed Rock and Coal
	Cloud 1	Cloud 2	Cloud 1	Cloud 2	Cloud 1	Cloud2	Cloud 1	Cloud 2	
0.2-0.4	6.9	9.2	12.5	8.4	13.6	14.7	15.3	11.8	38.4
0.4-0.8	39.6	28.9	29.3	28.9	20.5	24.7	25.3	28.4	25.0
0.8-1.2	30.4	23.8	29.6	30.0	33.0	23.7	13.7	20.8	17.7
1.2-1.6	13.5	15.9	13.2	19.1	13.9	19.3	8.7	14.5	11.9
1.6-2.0	4.9	14.0	5.5	5.1	10.1	8.8	18.9	7.8	2.2
2.0-2.5	3.9	9.1	1.8	3.4	6.5	5.9	7.9	3.9	3.0
2.5-3.0	0.4	1.9	2.4	3.9	2.4	2.3	3.6	3.3	1.4
3.0-4.0	-	2.5	1.7	0.7	-	0.3	3.2	1.9	0.2
4.0-5.0	0.2	2.3	2.3	0.5	-	0.3	1.7	2.8	0.2
5	0.2	2.4	1.7	-	-	-	1.7	4.8	-
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 17

	Silica Dust		Coal Dust		Fly Ash	
Blowing Period sec.	10	20	10	20	10	20
Dust Concentrations after one hour sedimentation	5600	17100	8720	16540	6840	18730
	6840	15200	6000	12000	7360	19110
	4890	16640	6500	13100	6340	14840
	5180	14160	7150	16500	9560	16500
	8250	14230	7150	15620	11160	13510
	6905	16890	5260	14420	6550	19650

spray efficiencies to be compared at similar dust concentrations and, as the range of particle size obtained in suspension is 0.2 micron to 6 microns, i.e. that believed to be most injurious to health and most difficult to remove, this laboratory apparatus enabled mining conditions to be reproduced.

Measurement of Particle Size

The size of a spherical particle is completely defined by its diameter but particles of irregular shape may be characterised in various ways. They depend on some particular property of the particle being considered. Different methods assess different size - dependent properties such as volume, surface or resistance to motion in a fluid or light scattering power. As the theories are derived for spherical particles, the size of an irregular particle is conveniently expressed as the diameter of the sphere, having the same volume or surface, etc. Only for spherical particles will the sizes by different methods be the same. In the case of irregular particles the sizes differ not only according to the method of measurement but also in some measurements according to the orientation of the particles, as for example, in the case of projected area.

It is usual to resort to an arbitrary statistical diameter. This is taken as the mean distance between the two extreme points of each particle when all particles lying at random are

measured in one fixed direction, i.e. the horizontal axis.

Microscope Method

The simplest method of determining the size of particles in the subsieve range (76 microns down to 0.2 micron) is by direct measurement of the dimensions of the magnified images as seen under a microscope. The measurements are generally made by visual comparison with the areas of images of reference circles which have been previously calibrated by means of a stage micrometer. The images are accurate magnifications of the particles and the microscope method is probably the most exact of all methods of sizing.

The size actually measured is the diameter of the circle having the same area as the unmagnified projected image of the particle, termed the area diameter.

When dust clouds contain a range of particle sizes a number distribution is obtained by plotting against small intervals of size, to derive a histogram, which in the limit becomes the size frequency curve. Since the shape of the curve depends on the interval chosen, it is preferable to plot number per unit size interval against size.

The mean value represents the particle size corresponding to the centre of area (centre of gravity) of the area enclosed by the curve and the x axis. The median value is the particle size at which the dust could be divided into two portions

of equal number and the mode represents the most frequently occurring particle size, that is, the particle size corresponding to the peak of the size distribution curve. The number mean particle size which corresponds to the centre of area of the size distribution curve is obtained from the expression $\Sigma(ND)/\Sigma N$.

Determination of Dust Concentration

In order to obtain the highest possible degree of accuracy (113,114) a Thermal Precipitator was used to collect samples of the dust clouds in the chamber. It is claimed to be 100 per cent accurate for 5 micron particles.

The samples were deposited on two cover glasses which were then mounted for evaluation on a microscope slide, by means of an acetone-ethyl acetate solution or a solution of commercial nail varnish which provided a complete seal preventing moisture condensing on the dust particles.

Samples were evaluated by counting the number of particles in a series of strips of known width on each cover glass.

Care was taken to traverse right across the deposit and to focus successively both on the underside of the cover glass and on top of the slide as a few large particles tended to fall from the cover glass and an appreciable air space generally existed between it and the slide.

If the length of the deposit is L mm., and the width of a traverse is W mm. there will be L/W traverses in each deposit. If the average count across the deposits from each side is N_1 and N_2, V being the volume of dust laden air sampled then the total number of particles per cubic centimetre is

$$\frac{N_1 + N_2}{V} \times \frac{L}{W}$$

At least 400 particles should be counted in each case to ensure the highest possible accuracy.

A Vickers Projection Microscope was used to evaluate the slides.

The limit of visibility depends on the objective employed, the method of illumination, the method of mounting and the nature of the particles.

A 2 mm. oil immersion objective of numerical aperture 1.3 with bright field illumination supplied by a mercury vapour lamp was used with a X10 compens ting eyepiece. This combination gave a magnification of x2400 enabling particles of 0.2 micron to be distinguished.

A Patterson-Cawood type graticle giving a closely spaced range of sizes was used to size the samples.

Before determining the effect of aqueous sprays on dust cloud

sedimentation it was necessary to study the natural sedimentation of the cloud under gravity.

Sedimentation and Aggregation of Dust Clouds

A particle suspended in a gas may move under the influence of the following forces :

(a) Forces which originate independently of the gas
(e.g. gravitation, centrifugal action, electric field)

(b) Forces which are the direct result of the molecular activity of the gas itself.
(e.g. Brownian Movement.)

A liquid or solid particle suspended in a gas is subjected to bombardment by the molecules of the gas. If the particle is large compared to the mean free path of the gas (i.e. $> 10^{-5}$cm.) the general effect of the molecular bombardment will be a uniform pressure exerted normally over the entire surface of the particle.

The ultimate settling velocity of particles $> 10^{-5}$cm. under gravity is given by Stoke's Law. It is assumed that for small particles there is streamlined flow of the fluid past the particle when there is relative movement between the two and the resistance to motion R is only effected by :

(a) Relative velocity (V)

(b) Particle diameter (d)

(c) Fluid absolute velocity (v)

Particle shape will, of course, have a bearing on the resistance to motion, but, at this stage, consideration is confined to particles of spherical shape.

By applying the theory of dimensions it can be shown that

$$R = KVdv$$

Stokes found that for spherical particles the value of K was 3π .

When a particle falls freely in a fluid it will quickly attain an ultimate or "terminal velocity" at which all further acceleration ceases. The force due to gravity is balanced by these resistive forces.

Thus, for small particles

$$3\pi Vdv = 4/3\pi r^3 (\rho_p - \rho_f) g$$

where ρ_p is the density of the particle and ρ_f the density of the fluid.

Non-spherical particles fall in the position in which they encounter maximum resistance. Thus fine crystals fall with their longer axis horizontal, similarly a cubic crystal falls point downwards, a plate or disc in a horizontal position (115).

For particles < 50 microns diameter, which are of primary concern in dust control work, terminal velocities are attained in a fraction of a second so that acceleration periods may be neglected.

Particles Smaller than the Mean Free Path of the Gas

Stoke's Law is, however, subject to a lower limit. When the dispersoid particle diameter approaches the mean free path of the gas molecules, the resistance to motion will be less than, and the settling velocity greater than, that which would be calculated from Stoke's Law. This is due to the tendency of the very small particles to slip between the molecules of the gas.

It has been shown by Cunningham (116) and Millikan (117) that

$V = V^1(1 + K \lambda/D)$ where V is the true velocity and V^1 the velocity corresponding to Stoke's Law, λ being the mean free path of the gas molecules and r the radius of the particles. K is a constant approximately equal to 0.86. The Cunningham correction on Stoke's Law becomes important for particles of diameter < 3 microns settling in gases.

The internal stability of a dust cloud is primarily dependent on the concentration which determines the rate of aggregation and on particle size which determines the settling rate.

It is well established both theoretically and experimentally (118, 119, 120) that Brownian movement causes coagulation of dust cloud particles at a rate proportional to the square of the number

concentration "n".

When this relationship holds, it means that all or nearly all particles adhere on collision. A number of reported results justify the assumption of 100 per cent collision efficiency of solid particles (119, 120, 121). Even in still aerosols, the observed coagulation is never less and is usually greater than that predicted by theory.

Concentrations of one million particles per cubic centimetre coagulate at the initial rate of 2 per cent per minute while a cloud of concentration 10,000 particles per cubic centimetre of 0.3 micron diameter will settle under gravity at the rate of 2 cm./hour and coagulate due to Brownian movement at the initial rate of one per cent per hour (122).

Kunkel (123) found on calculating the number of aggregates due to charged dust particles that aggregation is negligible if the cloud density is less than one million particles per cubic centimetre or if the average charge of one sign is well below 1,000 electrons per particle.

Whytlaw-Gray (124) and Glen (47) found an initial period lasting several hours (dependent on the initial dust concentration) during which the number of particles present in suspension decreased rapidly with time. This was followed by an intermediate period during which the decrease was not as

marked, leading to a final settling period when the change of concentration with time was very slight. These results can be explained in terms of the combined effect of natural sedimentation and aggregation.

Investigation of Dust Cloud Sedimentation

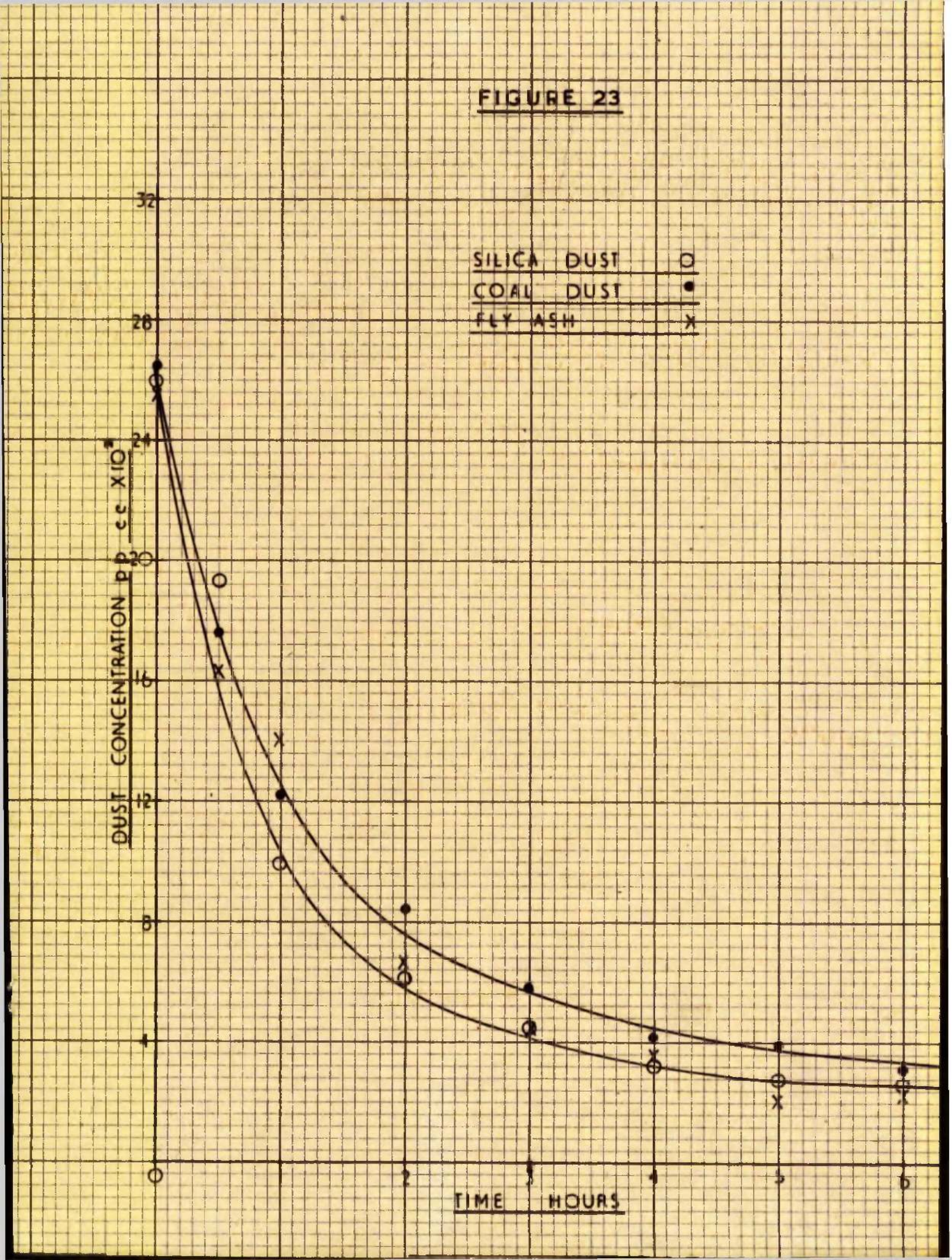
If the initial dust concentration was of the order of 10,000 particles per cubic centimetre and was 99 per cent 0.2 - 5 microns, the degree of aggregation would be negligible and the rate of sedimentation low. For this reason and in order to approach actual mining conditions the investigations described here were carried out with clouds of <u>ca</u> 7,000 particles per cubic centimetre.

Fig. 23 indicates that such a cloud with few aggregates can be obtained after 1½ hours sedimentation for each dust. At this point the flattening out of the curve indicates that the final or very slow settling period has commenced. The time of blowing was in each case 10 seconds. These curves were obtained by withdrawing samples from the cloud on formation and after ½ hour, 1 hour, 1½ hours, 2 hours, 3 hours, 4 hours, 5 hours and 6 hours sedimentation. The curves obtained were found to be reproducible.

Homogeneity of the Dust Cloud

It was necessary that both the concentration of the cloud

FIGURE 23


SILICA DUST O
COAL DUST •
FLY ASH X
DUST CONCENTRATION P.P.C.C. X10⁴
32
28
24
20
16
12
8
4
0
1
2
3
4
5
6
TIME HOURS

and its size distribution be uniform throughout the chamber. Since the cloud was initially formed by violent glowing, this was not likely to be the case at first. After a short period of time, however, the cloud should have become stable and the only movement should be that of particles falling under the gravitational pull and due to Brownian movement. For obvious reasons convection currents should be reduced to a minimum.

Samples of the dust clouds produced as described above were taken after 30 minutes, 60 minutes, and 90 minutes sedimentation at levels A, E and F corrections being made to compensate for alterations in concentration with time of sampling. A size analysis and count were carried out on each slide. Tables 18 and 19 show that both the concentration and size distribution of coal dust were fairly constant throughout the chamber after 90 minutes sedimentation. In Table 19 the experimental size distribution after 90 minutes is compared with that obtained by the application of Stokes Law to the 30 minute sedimentation experimental size distribution. The data would appear to indicate that there was little convection movement in the chamber. The foregoing results made the following assumptions possible

Table 18

Coal Dust Concentrations at Different Levels particles per cubic centimetre

Sedimentation Time	30 mins.		60 mins.		90 mins.	
Level	p.p.c.c.	percentage deviation from mean	p.p.c.c.	percentage deviation from mean	p.p.c.c.	percentage deviation from mean
A	17500	+1.16	9040	-0.33	6860	+6.14
B	16300	-5.80	9220	+1.65	6620	+2.42
F	18100	+4.64	8950	-1.32	5910	-8.52
Mean Value	17300		9070		6463	

Table 19

Percentage Size Distribution at Different Levels after 90 minutes Sedimentation (Coal Dust)

Position	A		E		F	
Size Range Microns	Exp	Calc	Exp	Calc	Exp	Calc
0.2-0.4	8.8	7.9	8.1	9.4	8.0	8.7
0.4-0.8	27.1	27.3	26.8	28.6	26.9	27.6
0.8-1.2	28.6	28.9	28.3	29.2	27.3	25.4
1.2-1.6	20.0	20.6	22.3	22.0	21.3	23.0
1.6-2.0	6.1	6.2	4.2	2.9	5.2	3.8
2.0-2.5	4.1	3.5	4.0	2.8	5.0	3.4
2.5-3.0	4.0	3.7	3.6	1.7	4.0	4.2
3.0-4.0	1.1	1.9	2.1	3.4	2.2	3.1
4.0-5.0	0.2	-	0.6	-	0.1	0.6
5.0	-	-	-	-	-	0.2
	100.0	100.0	100.0	100.0	100.0	100.0

(a) If, after forming a dust cloud, a sufficient interval is allowed to elapse a Thermal Precipitator sample withdrawn from the centre of the dust chamber is representative of the whole dust cloud in concentration and size distribution.

(b) The particle size distribution is constant throughout the chamber at any instant so that an accurate estimate of the change in distribution due to spraying can be obtained by comparing samples taken before and after the spray run. It is supposed that Stokes sedimentation is negligible during the period of spraying. The alteration of size distribution and concentration caused by spraying will render the prior sedimentation curve (Fig. 23) inapplicable beyond that point.

(c) The droplets retain their spherical shape irrespective of their size and vapour pressure.

Effect of Altering Spray Direction

Glen (47) found that no advantage was gained by altering the direction of spraying.

This would appear to be true for a stationary cloud, as

the same number and size distribution of droplets of the same initial velocity is obtained irrespective of the spraying direction. When a cloud is sprayed upwards any loss of suppression due to decrease in droplet velocity, through gravitational influence, is compensated for by the fact that once the droplets reach their maximum trajectory they will then fall downwards through the cloud removing more dust particles.

Effect of Spray Variables on Dust Suppression

The most easily controlled variable of the swirl atomiser is the atomising pressure. A change in it will alter the three main characteristics of the spray, viz :

(a) liquid throughput

(b) average droplet size

(c) droplet velocity

Each of these has an effect on the amount of dust suppressed by the spray.

According to Sell (125) the efficiency η of a water droplet in removing dust from suspension in air is given by

$$\eta = b^2/D^2$$

where D is a projected diameter of the droplet and b is the limiting diameter of the streamlines within which all particles will collide with and be captured by the droplet. This is shown

diagrammatically in Fig. 24.

Sell has also shown that the above efficiency is a function of the group

$$\frac{mv_r}{RD}$$

where m = mass of particle = $\rho \frac{\pi}{6} d^3$

ρ = particle density

d = particle diameter

v_r = relative velocity (in the same straight line) of droplet and particle

R = $3\pi\mu d$, for particles within the Stokes Law range

μ = gas viscosity

Then $\frac{mv}{RD} = \frac{1}{18} \frac{d^2 v_r \rho}{\mu D}$

From Sell's calculations it would appear that a relationship of the type

$$\eta = k\left(\frac{d^2 v_r \rho}{\mu D}\right)^p \qquad \text{holds}$$

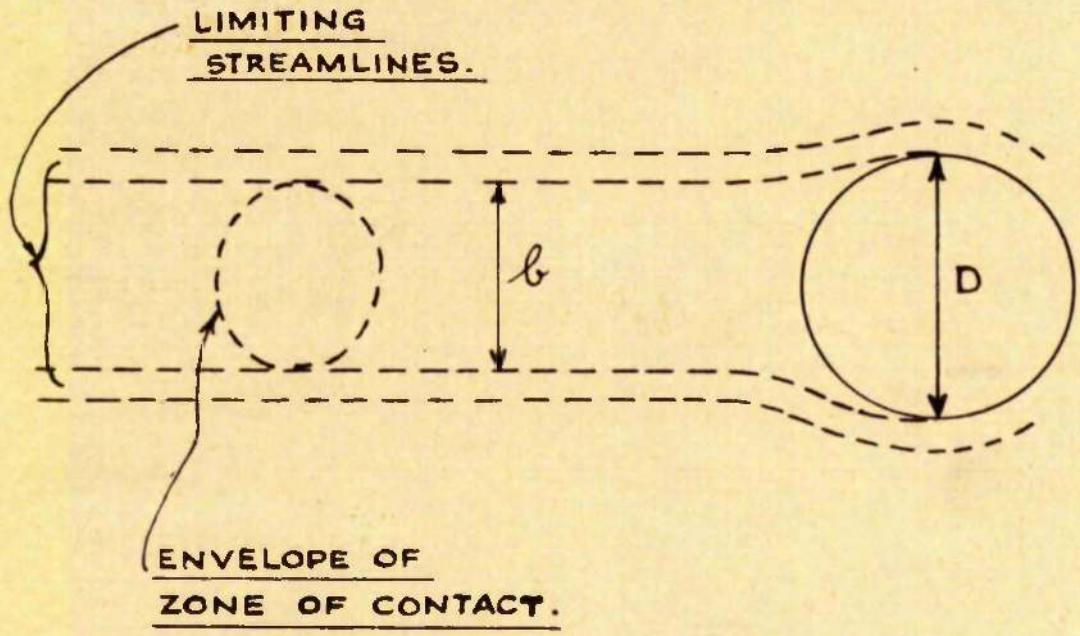
where k and p are constants the latter being less that 1.0.

This in a dust suppression test of the type carried out in the dust chamber the total number of dust particles knocked down during the spray run will be dependent on :

(a) the efficiency

(b) the number concentration of dust particles

FIGURE 24.



in unit volume of gas space

(c) the number of droplets produced per second

$$\propto \frac{\text{water throughput}}{(\text{average droplet size})^3}$$

(d) the distance gone by a droplet in passing through the dust cloud - assuming that a droplet collects many dust particles

(e) the time of spraying

(f) the cone angle - since this will control the dispersion of the droplets in air.

The rate of dust suppression should be related to the other variables in the following way

$$-\frac{dn}{dt} = k^1 \eta^p (n_0 - n) \frac{V}{D^3} L^q \alpha^s$$

where n_0 = initial dust concentration (particles per cubic centimetre)

n = dust concentration at time, t

V = water throughput (c.c. per second)

D = average droplet size (cm.)

L = length of droplet path (cm.)

α = cone angle

and k^1, p, q and s are constants.

In comparing sprays, therefore, where all other variables are kept steady the efficiency of dust suppression should be proportional to the relative velocity between dust particle

and droplet and the square of the average dust particle size and vary inversely with the average droplet size of the spray.

Effect of Atomising Pressure on Dust Suppression

Spray runs of 1 minute duration were carried out with nozzle A at various pressures, the dust clouds being formed as before. Table 20 shows that in each case the amount of dust suppressed increases with increase in atomising pressure, the amount knocked down being independent of the type of dust.

In an attempt to evaluate the effect of each of the three dependent variables mentioned earlier a series of tests was undertaken in which two of the three were in turn kept constant. On examination of the data obtained in Section 1 for throughputs and average droplet size, three nozzles were chosen which allowed either the droplet size or the velocity to be varied while the other factors remained unchanged. The throughput could be kept constant by adjusting the time of spraying. Tables 21 and 22 show the particular spray conditions necessary.

Effect of Altering Spray Throughput

This was determined for each dust using nozzle A and spraying at 60 lb./in.^{2} for varying periods. Those chosen were 30 seconds, 1 minute, 2 minutes, 5 minutes and 10 minutes. Tables 23, 24 and 25 show the percentage

Table 20

Pressure lb./in.^{2}	Dust Concentration particles per cubic centimetre		Percentage Reduction	Dust Concentration particles per cubic centimetre		Percentage Reduction	Dust Concentration particles per cubic centimetre		Percentage Reduction
	Before Spray	After Spray		Before Spray	After Spray		Before Spray	After Spray	
30	6000	4850	19.0	7704	6110	19.6	7450	5890	21.0
40	7642	5210	31.6	8206	5760	29.8	7681	5350	30.4
50	8152	4840	39.4	8624	5130	40.5	9120	5360	41.2
60	11360	5170	54.5	9175	4040	56.0	7150	3960	55.3
70	9030	3590	60.2	9116	3510	61.5	8913	3390	62.0
80	8611	3010	65.1	8222	2740	66.7	8052	2550	68.3
150	7983	1310	83.6	7650	1480	80.4	7887	1570	81.1

Table 21

Nozzle	Cone Angle	Pressure lb./in.²	Throughput c.c./min.	Average Droplet Size (Microns)	Duration of Spray	Velocity cm./min.
D	90	234	277.9	33	1 min.	43,240
A	60	30	55	80	5min.3 secs.	43,240
C	80	36	69.8	96	4 min.	43,240

Table 22

F	120	150	323	46	1 min.	20,100
C	80	75	96.5	46	3min.21 secs.	59,780
A	60	75	83	46	3min.54 secs.	65,250

reduction in dust concentration obtained in each case.

As is predicted from the differential equations derived in Page 80 the rate of knockdown decreases with time, shown in Fig. 25. The reduction obtained with a given volume of water appears to vary little with the type of dust in suspension, slightly poorer results being obtained for fly ash dust than for the others.

After 10 minutes spraying the remaining dust is found to be 98 per cent 2.5 microns and virtually unwettable unless very high contact velocities are employed. Thus 100 per cent removal at 60 lb./in.^{2} would never be achieved. 50 per cent of the dust cloud is removed in 1 minute.

Glen (47) has compared the percentage reduction in concentration (particles per cubic centimetre) with the reduction in surface area of the same dust obtained by a light extinction method and showed the percentage reduction in surface area to exceed that in number concentration. This would indicate that the larger particles and aggregates were preferentially removed.

An estimate of the efficiency of removal was obtained by dividing the number of dust particles removed by the number of spray droplets of average droplet size. This efficiency was termed the "effectiveness" measured in particles per droplet

Table 23

Coal Dust

Effect of Throughput

Average Droplet Size 46 Microns

Duration of Spraying	Pressure lb./in.^{2}	Dust Concentration particles per cubic centimetre		Percentage Reduction
		Before Spraying	After Spraying	
30 secs.	60	9450	5980	36.7
1 min.	60	11360	5170	54.5
2 mins.	60	7400	2400	67.7
5 mins.	60	7960	1920	76.0
10 mins.	60	9700	1700	82.4

Table 24

Silica Dust

Effect of Throughput

30 secs.	60	8060	5640	30.1
1 min.	60	9175	4040	56.0
2 mins.	60	9300	2620	71.9
5 mins.	60	6280	1832	70.0
10 mins.	60	7220	620	91.4

Table 25

Fly Ash

Effect of Throughput

30 secs.	60	7075	4880	31.0
1 min.	60	7150	4610	35.5
2 mins.	60	8900	4270	52.0
5 mins.	60	7200	2080	71.1
10 mins.	60	7507	736	90.2

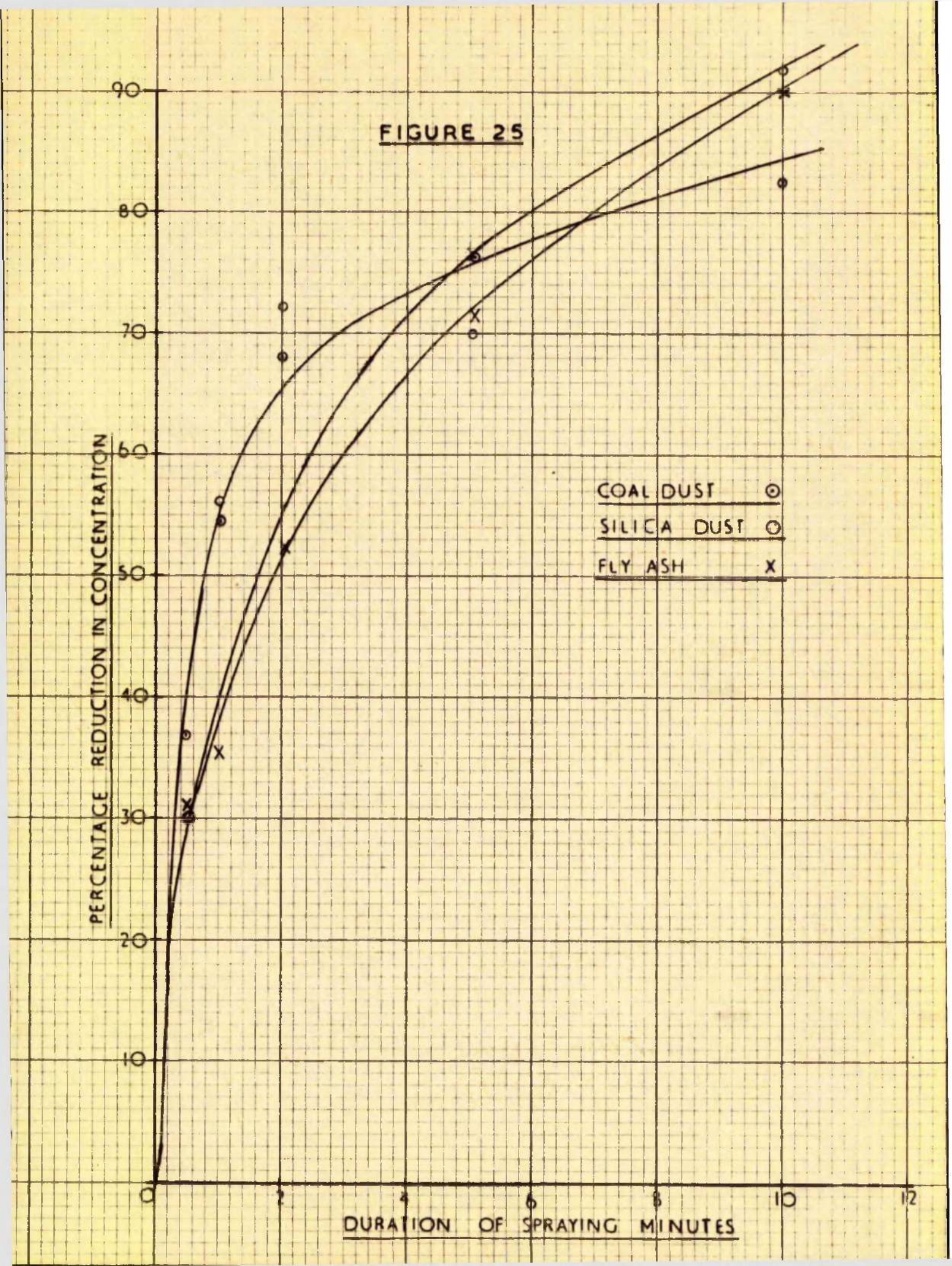


FIGURE 25
PERCENTAGE REDUCTION IN CONCENTRATION
90
80
70
60
50
40
30
20
10
0
2
4
6
8
10
12
DURATION OF SPRAYING MINUTES
COAL DUST ⊙
SILICA DUST O
FLY ASH X

and was calculated from

$$\frac{\Delta \text{ p.p.c.c. x vol. of chamber}}{\text{throughput (c.c./min.)}} \quad \frac{\text{vol. of average droplet}}{\text{duration of spray}}$$

Values given in Tables 21 and 22 were used in the calculations. The number of dust particles was in each case calculated back to a constant initial dust cloud of 7,000 particles per cubic centimetre .

These tables (26,27,28) show also that the "effectiveness" decreases rapidly with duration of spraying.

Effect of Droplet Size

The spray runs were carried out under the conditions given in Table 21 and the results Tables 29, 30 and 31 showed that the smaller the droplet size, the greater was the reduction in dust concentration obtained (over the range investigated) other factors being constant. The effect of droplet size appeared to be independent of the nature of the dust though slightly poorer results were obtained for the fly ash clouds. Examined under the microscope the fly ash particles appeared almost spherical in shape whereas the particles of silica and coal dust were very irregular. The results would appear to indicate that capture of the irregularly shaped particles was more efficient than that of the regular shapes.

Values of the "effectiveness" measured in particles per

Table 26

Coal Dust

Effect of Throughput

Average Droplet Size 46 Microns

Duration of Spraying	No. of Spray droplets	No. of dust particles removed per cubic centimetre	Effectiveness of removal (particles per droplet)
30 secs.	8.2104×10^8	2570	0.78556
1 min.	16.4208×10^8	3815	0.58306
2 mins.	32.8416×10^8	4730	0.36145
5 mins.	82.104×10^8	5311	0.16234
10 mins.	164.208×10^8	5773	0.08823

Table 27

Silica Dust

Effect of Throughput

30 secs.	8.2104×10^8	2103	0.64282
1 min.	16.4208×10^8	3918	0.5988
2 mins.	32.8416×10^8	5135	0.3924
5 mins.	82.104×10^8	4958	0.15156
10 mins.	164.208×10^8	6399	0.09779

Table 28

Fly Ash

Effect of Throughput

30 secs.	8.2104×10^8	2172	0.66392
1 min.	16.4208×10^8	2487	0.3801
2 mins.	32.8416×10^8	3641	0.27823
5 mins.	82.104×10^8	4977	0.15179
10 mins.	164.208×10^8	6314	0.09649

Table 29

Coal Dust

Nozzle	Average Droplet Size Microns	Dust Concentration Particles per cubic centimetre		Percentage Reduction
		Before Spraying	After Spraying	
D	33	6390	826	87
A	80	6320	1890	70
C	96	4520	1855	59

Table 30

Silica Dust

D	33	10790	1890	82.5
A	80	9180	2670	70.9
C	96	11390	4984	56.2

Table 31

Fly Ash

D	33	8550	2552	70.2
A	80	7300	3460	52.6
C	96	10700	6440	40.0

droplet are given in Tables 32, 33 and 34. They contradict those given in Tables 29, 30 and 31 which only give and estimate of the percentage dust removed. In Tables 32, 33 and 34 the number of droplets utilised in each run is being taken into account and therefore presents a truer picture of the situation. These tables show that the smaller droplets are least efficient in particle knockdown agreeing with the theoretical conclusions of Davies (126). The results show that for a threefold increase in average droplet size, 33 microns to 96 microns, the efficiency of collection increased by a factor of 10. It would therefore appear that an optimum value of droplet size existed possibly > 96 microns.

Again the values obtained for fly ash suppression were slightly poorer than those obtained for the other dusts.

Effect of Droplet Velocity

The velocity of the water droplets issuing from the nozzle was determined by assuming that the spray orifices "ran full". This assumption is not valid for swirl atomisers of the type used, but as the assumptions were applied to all the nozzles comparative velocities were obtained. The velocities employed in this work were obtained by spraying under the conditions given in Table 22.

The effect of velocity as seen from Tables 35, 36 and 37

Table 32

Coal Dust

Effect of Droplet Size

Average Droplet Size Microns	No. of Spray Droplets	No. of dust particles removed per cubic centimetre	Effectiveness of Removal (particles per drop)
96	6.026×10^{8}	4128	1.17192
80	1.036×10^{9}	4907	1.11887
33	1.477×10^{10}	5943	0.10098

Table 33

Silica Dust

Effect of Droplet Size

96	6.026×10^{8}	3937	1.16397
80	1.036×10^{9}	4965	1.12028
33	1.477×10^{10}	5773	0.098093

Table 34

Fly Ash

Effect of Droplet Size

96	6.026×10^{8}	2787	1.11607
80	1.036×10^{9}	3683	0.77706
33	1.477×10^{10}	4911	0.072687

is not as great as was expected, the gain in suppression obtained with a velocity increase of 45,000 cm./min. being only 10 per cent, slightly lower again in the case of fly ash.

Values of the "effectiveness" are given in Tables 38, 39 and 40. As before a velocity increase of 45,000 cm./min. is associated with only a slight increase in collection efficiency.

Combined Effects of Velocity and Droplet Size

The improvement in suppression brought about by increasing the throughput has been shown to be limited. Droplet size and velocity played a much more important part in the suppression process although it is not clearly shown in Tables 29 - 37 which had the greater effect. It was considered necessary to determine which was more effective over the range investigated.

A selection of values obtained by spraying under some of the conditions given in Tables 21 and 22 is shown in Tables 38, 39 and 40. The "effectiveness" of removal expressed as particles per drop is taken as the most representative criterion and is compared in each case for coal dust, silica dust and fly ash.

They show that if a spray of average droplet size 33 microns is used in place of one of average droplet size 46 microns a much lower "effectiveness" of removal is obtained despite the fact that the droplet velocity is doubled. An increase in droplet

Table 35

Coal Dust

Effect of Velocity

Nozzle	Average Droplet Size Microns	Dust Concentration Particles per cubic centimetre		Percentage Reduction
		Before Spraying	After Spraying	
A	65250	5180	1410	72.8
C	59780	5880	1550	73.6
F	20100	5820	1845	68.3

Table 36

Silica Dust

Effect of Velocity

A	65250	10750	2450	77.2
C	59780	11930	2391	80.0
F	20100	11000	2210	79.9

Table 37

Fly Ash

Effect of Velocity

A	65250	9710	2520	74.1
C	59780	7620	2165	71.6
F	20100	8550	2880	66.3

Table 38

Coal Dust

Effect of Velocity

Velocity cm./min.	Average Droplet Size Microns	No. of Spray Droplets	No. of dust particles removed per cubic centimetre	Effectiveness of removal (particles per drop)
65250	46	6.3515×10^{9}	5102	0.20160
59780	46	6.3432×10^{9}	5154	0.20392
43240	33	1.477×10^{10}	5942	0.10098
20100	46	6.3378×10^{9}	4781	0.18935

Table 39

Silica Dust

Effect of Velocity

65250	46	6.3515×10^{9}	5404	0.21353
59780	46	6.3432×10^{9}	5595	0.22137
43240	33	1.477×10^{10}	5773	0.09807
20100	46	6.3378×10^{9}	5594	0.22152

Table 40

Fly Ash

Effect of Velocity

65250	46	6.3515×10^{9}	5185	0.20488
59780	46	6.3432×10^{9}	5011	0.19823
43240	33	1.477×10^{10}	4911	0.07269
20100	46	6.3378×10^{9}	4642	0.18382

size of 13 microns has therefore a much greater effect on suppression than a velocity increase of 20,000 cm./min. The suppression process is therefore more sensitive to small changes in droplet size and it may well be that the optimum droplet size is therefore not much greater than 100 microns.

Possibly a velocity increase of 20,000 cm./min. on 20,000 cm./min. is not significant and it would in fact require to be of the order of 20,000 times 20,000 cm./min. to produce a marked effect. However, at this velocity (i.e. 4×10^8 cm./min.) the effect would not simply be due to droplet velocity but be composed of velocity increase and turbulence, the latter having by far the greatest effect in bringing about collision.

Parameters and Nature of Flow Pattern

The relative velocity v_r between dust particle and droplet is impossible to measure accurately and thus velocity functions have been used by many workers.

Stairmand (127) employed the dimensionless group

$\frac{dg}{vf}$ as a basic parameter

where d = particle diameter

g = gravitational constant

v = velocity of dust particle relative to droplet

f = the free falling speed of the particle

He claimed that the maximum efficiency for the smaller dust particles occurred with droplet sizes of about 800 microns and that the efficiency varied little over the range of drop sizes from 500 to 1000 microns except for the very finest dust particles.

Assuming the droplet velocity to be that of the flow stream at 60 lb./in^2 pressure and dust particles of diameter 0.5 and 50 microns to be knocked down by droplets of 10 and 100 microns diameter, values of this parameter were calculated and are given in Table 41.

Davies (126) employed a "so-called" particle parameter (P) which is inversely proportional to the droplet diameter, particles of a given size having a smaller value of P relative to the larger droplets. He found impingement efficiency to decrease with P and this effect to outstrip the increase in droplet terminal velocity, which is very slight for droplets greater than D = 4000 microns, so that above an optimum value impingement upon large droplets actually decreased as drop size increased. In later work he collaborated with Peets (128) and they used a similar expression. Values of this parameter are also given in Table 41.

A parameter shown below, again proportional to the droplet diameter, was adopted by Fonda and Herne (129), Taylor (130), and Langmuir (131) in their calculations of droplet

Table 41

Parameter Values

Size of Dust Particles (Microns)	Stairmand		Davies		Fonda and Reme, Taylor and Langmuir	
	10 micron droplet	100 micron droplet	10 micron droplet	100 micron droplet	10 micron droplet	100 micron droplet
0.5	1.7088×10^{-4}	2.05×10^{-5}	5.813	5.813×10^{2}	1.878×10^{3}	1.878×10^{2}
5.0	1.7088×10^{-5}	2.05×10^{-6}	5.813×10^{-3}	5.813×10^{1}	1.878×10^{5}	1.878×10^{4}

trajectories

$$K = \frac{2\rho r^2 v}{9\eta R}$$

It is dimensionless with

v = the fluid velocity relative to the sphere at large distances from the sphere

η = the absolute viscosity of the fluid (air)

ρ = the density of the fluid (air)

r = the effective spherical radius of the particle

R = the droplet radius

Calculated values for the conditions stated are included in Table 41.

The efficiency of collection, taken from Stairmand's curve of efficiency versus values of his basic parameter, corresponding to the calculated values given in Table 41, are of the order of 100 per cent. This agrees well with the experimental values previously determined (Tables 23 - 40).

Stairmand (127), however, showed that the highest efficiencies were obtained when the value of the parameter and consequently the particle diameter was small. This was in direct contrast to the findings of Davies (126) and all experimental work reported has shown that removal becomes more difficult when the particle diameter is 5 microns.

Values of the Davies and Peets (126) parameter in Table 41 are quite large and the flow conditions therefore may be assumed to be turbulent. Dust suppression under these conditions is claimed by them to be of a high order. As the parameter for a 100 micron droplet is much greater than that for a 10 micron droplet (Table 41) the suppression may be considered more efficient the larger the droplet size up to at least 100 microns. This again agrees with experimental results.

To be captured and carried down, all particles must pass into the limiting diameter of the droplet (see Fig. 24.) Taylor (130) and Langmuir (131) have shown that there is a limiting value of the parameter below which all infinitesimal particles are wholly deflected round a finite obstacle. This critical value depends on the shape of the obstacle i.e. the flow pattern round it, and for the potential flow assumed to hold in the experiments carried out, discussed in later paragraphs, is about 10^{-1}. For the above conditions the calculated parameter values are high (Table 41.) and therefore efficiency of removal, as is the case, should be high.

The results given in Tables 23 - 40 show that the "effectiveness" is reasonably large confirming these theoretical conclusions.

The flow pattern of a droplet approaching a particle in suspension is shown in Fig. 24. When a droplet laden fluid

impinges on a body the fluid (air) will be deflected round the body whereas the droplet because of its greater inertia will impinge upon it. The inertia will of course increase with the size of the droplet.

The nature of the flow past the dust particle will therefore exercise a considerable influence on the paths taken by the droplets. When Reynolds Number is small the streamlines will spread outwards to pass round the particle very gradually. Davies and Peets (126) in their calculations of trajectories found that at the value of 0.2 (viscous flow) there is a 3 per cent disturbance as far as 200 diameters upstream, whereas the effect of the obstacle (dust particle) is hardly apparent 2 diameters away in potential flow. Even under turbulent conditions the flow on the upstream side of the obstacle should approach potential flow.

In the dust chamber the droplets have initially a velocity such that Reynolds Number is about 1000 (i.e. potential flow region), and after the first wave of droplets has passed into the cloud, turbulence will be set up and is maintained until spraying ceases.

The Kinetics of Dust Suppression

When a dust cloud in suspension is sprayed we might consider the contact of a droplet and particle to be similar to a chemical

reaction, viz :

1 particle + 1 droplet = knockdown

Depending, however, on the conditions, the relative sizes, relative velocity etc., one droplet may knock down two or more particles and the equation for the " reaction " would then become

n particles + 1 droplet = knockdown

Again, depending on the droplet size, more than one droplet may be required to knock down one dust particle. If account is taken of the number of molecules of the reactants involved an " order of reaction " may be determined for the process. The " reaction " may also be considered " irreversible," the dust particles knocked down being removed from the reaction area and the rate of reaction may be expressed as the rate of disappearance of dust. This rate of dust removal has already been related to the variables in the system by the differential equation given on Page 80.

Chemical reactions are classified into first, second, third and higher orders according to the number of molecules which appear to enter into the reaction, as determined by the relationship existing between the rate and the reactant concentrations. The suppression process is unlikely to follow a first order reaction as we can consider at least two

"molecules", one dust particle and one droplet, to be involved in the process. The reaction must therefore conform to a second or higher order.

Mathematical rate equations for various orders have been developed. There are several methods of determining the order of a reaction but the following two mentioned by Mee (132) seemed to be most readily applicable in this work. The first was to determine the products of the reaction, or dust concentration from time to time and substitute the values in the various order equations.

The second was to determine the time required for a fraction of the reaction to be completed, say one-half of it. Mathematical treatment showed that the time for half change for reactions of different orders was inversely proportional to the concentration raised to the power of the order minus one.

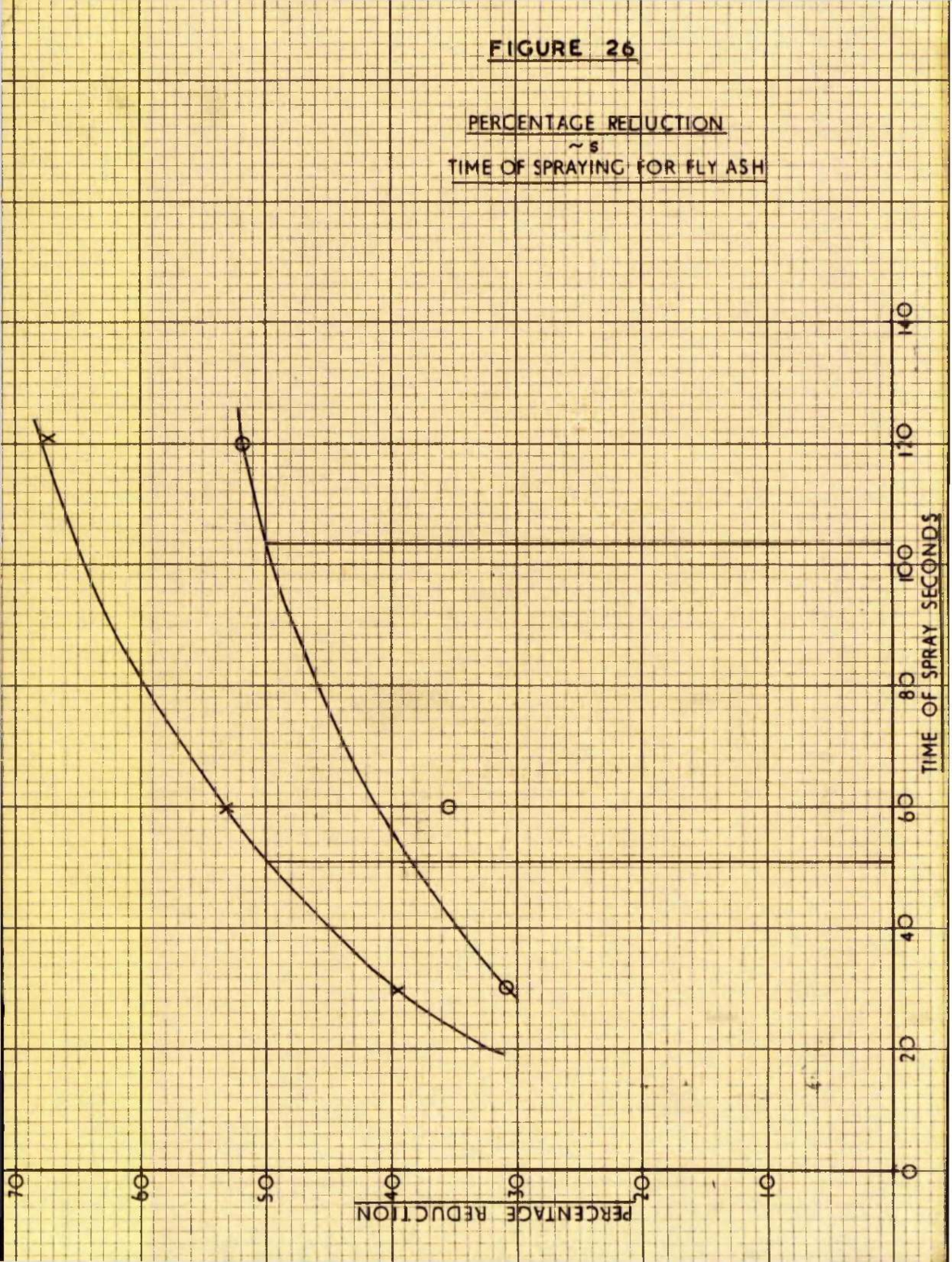
Thus the time for half change is independent of concentration, for a unimolecular reaction, whilst it is inversely proportional to the concentration for a bimolecular reaction, and inversely proportional to the square of the concentration for a termolecular reaction. Thus, if the times at which the reaction is half completed, t_1 and t_2 are determined for respective initial concentrations of c_1 and c_2, the equation connecting them is

$$t_2/t_1 = (c_1/c_2)^{n-1}$$

where n is the order.

FIGURE 26

PERCENTAGE REDUCTION ~ s TIME OF SPRAYING FOR FLY ASH



This being so the reciprocal of the dust concentration measured after any period of spraying should, when plotted against the time of spraying, lie on a straight line.

The order was verified and also shown to hold for coal dust and silica dust at 60 lb./in.^{2} by plotting the values obtained for the effect of spray throughput on the dust clouds shown in Tables 23, 24 and 25. The values for the silica dust cloud are shown plotted in Fig. 27.

To determine the effect of atomising pressure on the order of reaction spray runs were carried out on coal dust clouds using nozzle A at 30 lb./in.^{2} The values obtained after different periods of spraying are tabulated below calculated to a constant initial dust cloud of 8,720 particles per cubic centimetre.

Table 43

Coal Dust

Constant Average Droplet Size

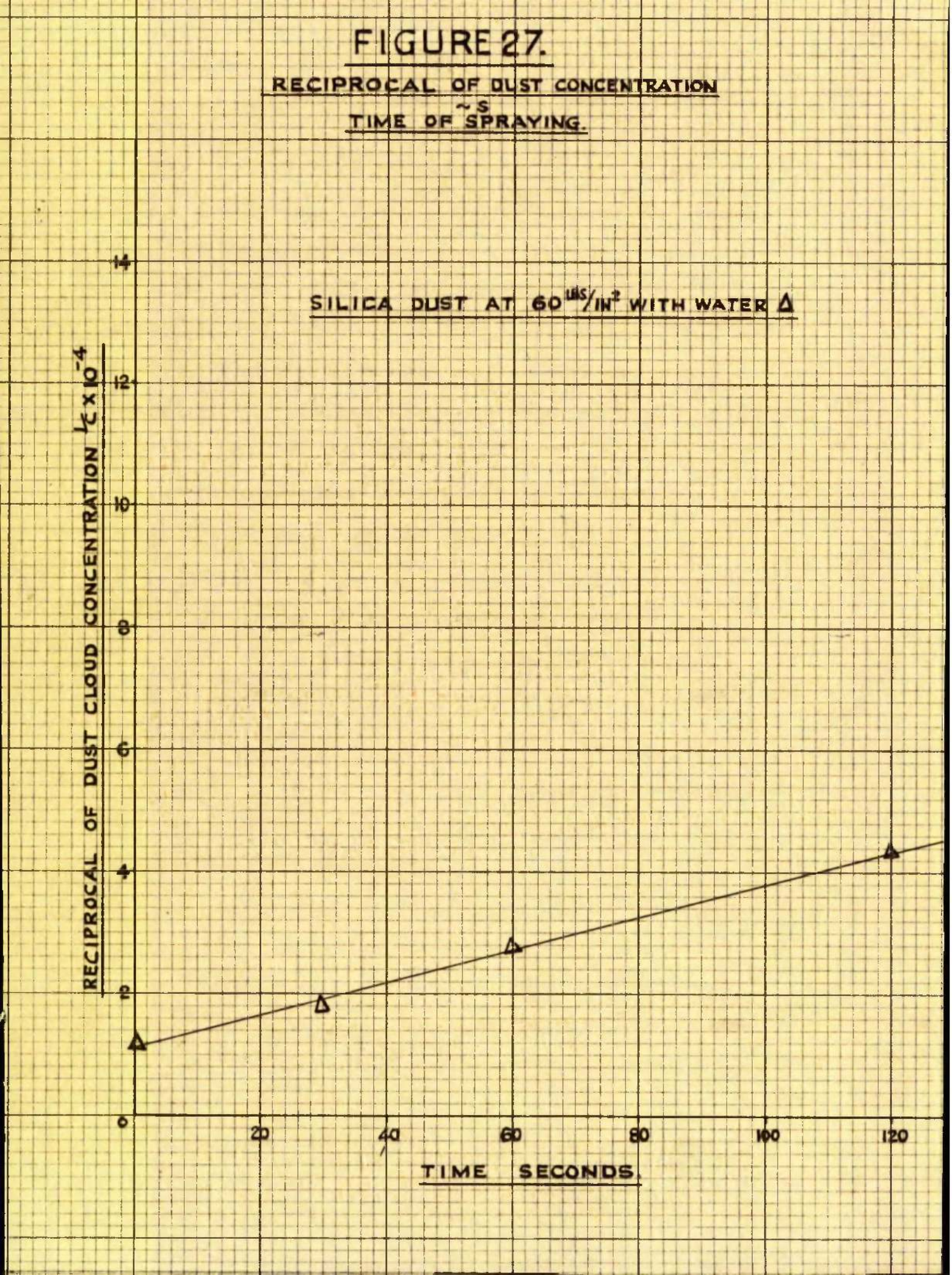
Duration of Spraying	Dust Cloud concentration after spraying	Reciprocal of concentration $\times 10^{-4}$
0	8720	1.147
30 secs.	7100	1.408
1 min.	7040	1.420
2 mins.	5010	1.996
5 mins.	4000	2.500

FIGURE 27.

RECIPROCAL OF DUST CONCENTRATION

~S

TIME OF SPRAYING.



A plot of the reciprocal of the dust cloud concentration against time of spraying again showed that the process conformed to a second order reaction. Analogous results have been obtained for all the dusts employed (coal dust, silica dust and fly ash).

It would therefore appear that on average one droplet knocks down one dust particle. This would appear to confirm the values obtained for the " effectiveness" given in Tables23 -40.

This offers a means of indirectly determining the water required to reduce the dust concentration to a certain level. If it were required to reduce the concentration of airborne silica dust by water sprays to 10 particles per cubic centimetre the equation of the straight line in Fig. 27 can be used to determine the time of spraying required. Taking the curve shown in Fig. 27 which is $y = 2.67 \times 10^{-6} x + 1.2 \times 10^{-4}$ the required value of x would be obtained by substituting the appropriate value of y, the reciprocal of the dust concentration. The required time is therefore 623 minutes.

SECTION 4

Effect of Surface-Active Agents on the Amount of Dust Suppressed

In Section 2 it was found that at high spray pressures no improvement in atomisation was gained by using liquids of low surface tension. Such liquids should allay dust more effectively than water owing to the improved wetting obtained.

To determine the effect of surface-active agents on the dust in the chamber, tests were carried out using some of the low surface tension liquids previously employed in Section 2. Liquids were selected to give a range of composition and surface tension value. The equilibrium surface tensions desired were obtained using the appropriate concentrations from Fig. 17 and are shown in Table 14.

Spray runs were carried out as before at a pressure of 60 lb./in^2. with the various liquids, the duration of spraying in each case being exactly one minute. The results shown in Tables 44, 45 and 46 were obtained.

The "knockdown" expressed as percentage reduction in dust concentration showed that most of the surface-active agents, irrespective of equilibrium liquid surface tension, had virtually the same effect as that of water. Calcium chloride solution was much less effective than pure water with each dust. The highest "knockdown" values were obtained using cyclohexane.

Values for the "effectiveness" of removal calculated from

Table 44

Coal Dust — Pressure 60 lb./in² — Nozzle A for 1 minute

Liquid	Surface Tension dynes/cm	Average Droplet Size Microns	Dust Concentration p.p.c.c. Before Spray	Dust Concentration p.p.c.c. After Spray	Percentage Reduction
cycloHexane	25.3	49.1	6550	2210	66.0
K-PE	23.5	58.3	8240	4420	49.0
Sod. laurate (aq.)	33.0	54.7	7930	4380	44.7
Sod. oleate (aq.)	33.0	54.0	7410	3094	58.2
iso-Amyl alcohol(aq.)	33.0	59.2	7690	3450	55.0
iso-Butyl alcohol(aq.)	33.0	54.0	5660	2500	55.9
Sod. chloride (aq.)	82.5	53.5	8000	3560	55.5
Calcium chloride(aq.)	82.5	51.2	7680	6480	15.5
Water	72.5	53.0	11360	5170	54.5

Silica Dust — Table 45 — Pressure 60 lb./in²

cycloHexane	25.3	49.1	5238	1585	69.8
K-PE	23.5	58.3	8250	2043	50.5
Sod. Laurate(aq.)	33.0	54.7	5405	3220	40.6
Sod. Oleate (aq.)	33.0	54.0	6930	4360	37.0
iso-Amyl alcohol(aq.)	33.0	59.2	7135	2550	64.2
iso-Butyl alcohol(aq.)	82.5	54.0	6660	3860	42.1
Sod. chloride (aq.)	82.5	53.5	8770	4010	54.3
Calcium chloride(aq.)	82.5	51.2	9000	6070	32.5
Water	72.5	53.0	9175	4040	56.0

Fly Ash — Table 46 — Pressure 60 lb./in²

cycloHexane	25.3	49.1	6700	2730	59.1
K-PE	23.5	58.3	9075	4660	48.6
Sod. laurate (aq.)	33.0	54.7	9040	6170	30.7
Sod. oleate (aq.)	33.0	54.0	8650	5700	34.0
iso-Amyl alcohol(aq.)	33.0	59.2	9450	3960	58.1
iso-Butyl alcohol(aq.)	33.0	54.0	7120	4080	42.7
Sod.chloride (aq.)	82.5	53.5	7550	4935	34.6
Calcium chloride(aq.)	82.5	51.2	9650	6825	29.4
Water	72.5	53.0	7150	4610	35.5

the total number of average droplets sprayed in one minute and the number of dust particles removed are given in Tables 47, 48 and 49. They show little variation from the value for water. As would be expected aqueous calcium chloride gives the lowest result. Rather surprisingly cycloHexane shows no improvement over water. On the other hand, the solution of iso-Amyl alcohol would appear to be almost 50 per cent more effective than water.

Effect of Surface-Active Agents at Low Atomising Pressure

The results in Section 2 showed that the effect of low surface tension on average droplet size was more apparent at low pressures. Surface-active agents should therefore be more effective dust suppressive agents than water at this pressure.

Tables 50, 51 and 52 indicate the values obtained for the percentage reduction in dust concentration. In the case of coal dust greater "knockdown" is provided by cycloHexane and sodium oleate solutions while for the other dusts, except in the case of cycloHexane, there is no clear indication of the relative merit of the liquids.

Tables 53, 54 and 55 again show the effectiveness of removal of dust at 30 lb./in.^{2} The values can be seen to be higher than those for 60 lb./in.^{2}, indicating perhaps the advantage of using large droplets of water. There is no obvious indication as to which liquid is the most effective

Table 47

Coal Dust — Pressure 60 lb./in.^{2} — Nozzle A

Liquid	No. of spray droplets in 1 min.	No. of dust particles removed-c.c.	Effectiveness of Removal (particles per drop)
cycloHexane	11.775 x 10^8	4638	0.9884
K-PE	7.0358 x 10^8	3245	1.1575
Sod. laurate (aq.)	8.5182 x 10^8	3133	0.9231
Sod. oleate (aq.)	8.849 x 10^8	4077	1.1563
iso-Amyl alcohol (aq.)	6.717 x 10^8	3859	1.4419
iso-Butyl alcohol (aq.)	8.849 x 10^8	3909	1.1086
Sod. chloride (aq.)	10.39 x 10^8	3885	0.9384
Calcium chloride(aq.)	9.802 x 10^8	1094	0.2801
Water	9.367 x 10^8	3815	1.0221

Silica Dust — Table 48

cycloHexane	11.775 x 10^8	4881	1.04
K-PE	7.0358 x 10^8	3534	1.2606
Sod. laurate (aq.)	8.5182 x 10^8	2829	0.8335
Sod. oleate (aq.)	8.849 x 10^8	2527	0.7365
iso-Amyl alcohol (aq.)	6.717 x 10^8	4409	1.6809
iso-Butyl alcohol (aq.)	8.849 x 10^8	2943	0.834
Sod. chloride (aq.)	10.39 x 10^8	3799	0.9176
Calcium chloride (aq.)	9.802 x 10^8	2279	0.835
Water	9.367 x 10^8	3918	1.0497

Fly Ash — Table 49

cycloHexane	11.775 x 10^8	4148	0.8839
K-PE	7.0358 x 10^8	3405	1.2146
Sod. laurate (aq.)	8.5182 x 10^8	2223	0.6549
Sod. oleate (aq.)	8.849 x 10^8	2387	0.6770
iso-Amyl alcohol(aq.)	6.717 x 10^8	4066	1.5191
iso-Butyl alcohol (aq.)	8.849 x 10^8	2989	0.8477
Sod. chloride (aq.)	10.39 x 10^8	2411	0.5824
Calcium chloride (aq.)	9.802 x 10^8	2049	0.5246
Water	9.367 x 10^8	2487	0.6663

Coal Dust — Table 50 — Pressure 30 lb./in.^{2}

Liquid	Surface Tension dynes/cm	Average Droplet Size Microns	Dust Concentration p.p.c.c. Before Spray	After Spray	Percentage Reduction
cycloHexane	25.3	49.1	7440 4920	2070 1112	72.2 77.3
Sod. oleate (aq.)	33.0	54.0	5918	4400	25.0
Iso-Amyl alcohol(aq.)	33.0	59.2	8610	4900	43.1
Sod. chloride (aq.)	82.5	53.5	4900	2120	56.8
Water	72.5	53.0	4490	3500	32.0

Silica Dust — Table 51 — Pressure 30 lb./in.^{2}

cycloHexane	25.3	49.1	6526	1518	76.7
Sod. oleate (aq.)	33.0	54.0	8870	5550	37.5
Iso-Amyl alcohol (aq.)	33.0	59.2	9860	6730	31.7
Sod. chloride (aq.)	82.5	53.5	5305	2850	46.3
Water	72.5	53.0	5305	2750	47.9

Fly Ash — Table 52 — Pressure 30 lb./in.^{2}

cycloHexane	25.3	49.1	9300	4116	55.8
Sod. oleate (aq.)	33.0	54.0	8410	5900	30.1
Iso-Amyl alcohol(aq.)	33.0	59.2	9650	4262	55.8
Sod. chloride (aq.)	82.5	53.5	8760	8050	8.0
Water	72.5	53.0	7136	5425	25.0

Table 53

Coal Dust — Pressure 30 lb./in.^{2} — Nozzle A

Liquid	No. of spray droplets in 1 min.	No. of dust particles removed-c.c.	Effectiveness of Removal (particles per drop)
cyclohexane	2.9852×10^8	5053 5418	4.2484 4.5553
Sod. oleate (aq.)	2.1715×10^8	1795	2.0745
iso-Amyl alcohol (aq.)	1.8504×10^8	3016	4.0906
Sod. chloride (aq.)	1.4171×10^8	3971	7.0325
Water	2.051×10^8	1542	1.8868

Silica Dust — Table 54

cyclohexane	2.9852×10^8	5372	4.5166
Sod. oleate (aq.)	2.1715×10^8	2620	3.028
iso-Amyl alcohol (aq.)	1.8504×10^8	2223	3.015
Sod. chloride (aq.)	1.4171×10^8	3239	5.7361
Water	2.051×10^8	3371	4.1248

Fly Ash — Table 55

cyclohexane	2.9852×10^8	3906	3.284
Sod. oleate (aq.)	2.1715×10^8	2089	2.4143
iso-Amyl alcohol (aq.)	8504×10^8	3909	5.301
Sod. chloride (aq.)	1.4171×10^8	1567	2.7751
Water	2.051×10^8	1688	2.0654

with all dusts.

Anomalous Effect of cycloHexane

cycloHexane appears to give the greatest reduction in dust concentration.

To investigate further this property of cycloHexane it was decided to determine the solubility of the dusts in this fluid and its dispersive (or wetting) power.

Determination of Solubility

The dust used was the same as that employed in the suppression experiments (99 per cent $<$ 5 microns). Temperature was maintained at 20° in an air thermostat, within which a shaft rotated at 30 r.p.m. Eighteen tubes of 50 ml. capacity were clipped to this shaft and the materials kept in continuous agitation. The mass/liquid ratio was kept constant at 5 gm. dust/40 ml. liquid during the estimations. Comparative solubility results (in mgm./100 ml.) were thus obtained for the dusts in cycloHexane and water after 6 hours, 24 hours and 72 hours and are given in Table 56.

This gravimetric method although relatively inaccurate shows that the solubilities of the dusts in water and cycloHexane can be taken as zero after 3 days contact. Any solution effect on the airborne dust would have to be instantaneous to affect a "knockdown".

Table 56

Time	Coal Dust		Silica Dust		Fly Ash	
Hours	Water	cyclohexane	Water	cyclohexane	Water	cyclohexane
6	NIL	NIL	NIL	NIL	NIL	NIL
24	NIL	NIL	NIL	NIL	NIL	NIL
72	0.3	0.4	0.2	0.3	0.3	0.2

Table 57

Liquids	Surface Tension dynes/cm.	Coal Dust	Silica Dust	Fly Ash
cyclohexane	25.3	9.4	12.5	9.6
iso-Amyl alcohol(aq)	33.0	3.1	2.8	3.4
Water	72.5	2.7	3.3	2.3

It has of course been shown by several workers that even soluble aerosols can be difficult to wet. Sulphuric acid mist and Ammonium chloride consists of particles or droplets which are very soluble once collected but can be passed through a series of gas washing bottles and escape as a dense white cloud (133).

Dispersive Property of cycloHexane

Many workers have studied the dispersion of dusts in various liquids (134, 135).

Slide Preparation

This was carried out by stirring a weighed quantity of the fine dust in a suitable volume of liquid (cycloHexane, iso-amyl alcohol solution or water) removing a drop of constant volume and placing it on a clean microscope slide. The slide was allowed to dry out of contact with the air. When dry a clean cover slip was placed over it and fixed in position. The volume of the drop of liquid was kept constant in each case so that approximately the same weight of dust was evenly dispersed in each case.

Counting

Counting was done using the Vickers Projection Microscope with a magnification of X 1120. The number of single dust particles and the number of aggregates within the area of a

standard graticule were estimated. A number of graticule area counts were made traversing the slide horizontally until at least 400 single particles had been noted. The results shown in Table 57 are expressed as the number of dust particles per aggregate in each case. This gives an estimate of the number of particles freely dispersed in a fixed area in any one medium per aggregate found therein.

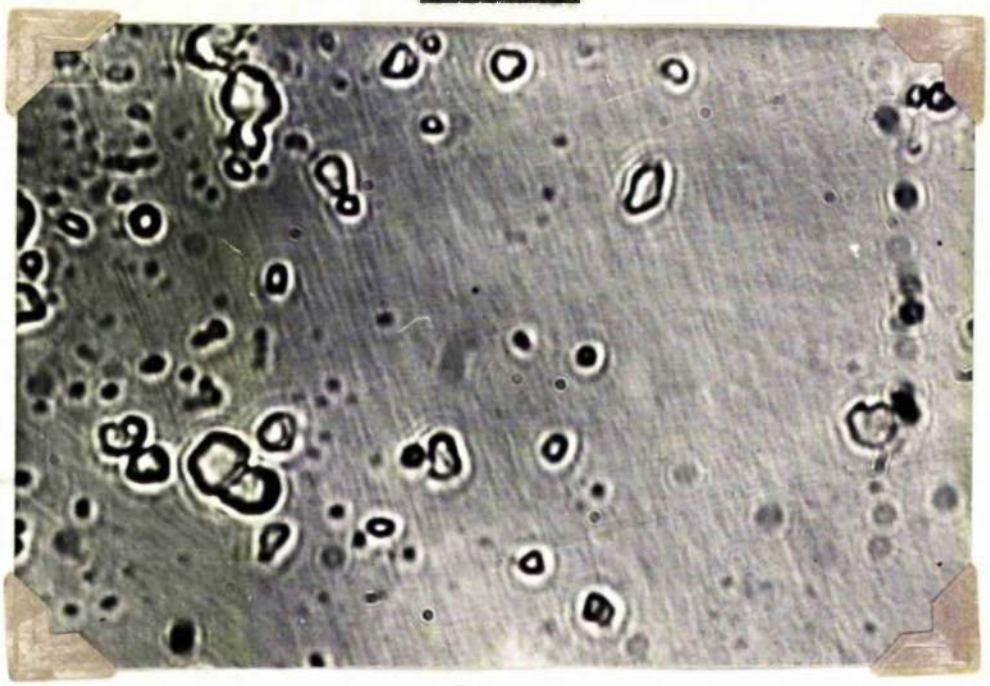
Results

The results show a tendency for the dust particles to be more evenly dispersed in cyclohexane than in water or iso-amyl alcohol solution. The indication is that the dusts are more thoroughly wetted by cyclohexane, which since it is in the equilibrium state will have a surface tension value of 25.3 dynes/cm. iso-amyl alcohol solution has a surface tension of 33 dynes/cm. and water 72.5 dynes/cm. The water as can be seen from Fig. 28a is not wetting the dust thoroughly allowing the particles to form large aggregates. This property of water, especially with respect to coal dust, has long been known. Fig. 28b. shows the particles to be much more evenly dispersed in cyclohexane.

Although the dispersivity appears to give a reasonable explanation of the unique ability of cyclohexane to allay dusts the results are not conclusive.

No obvious advantage was gained in any other case by using surface-active agents.

FIGURE 28



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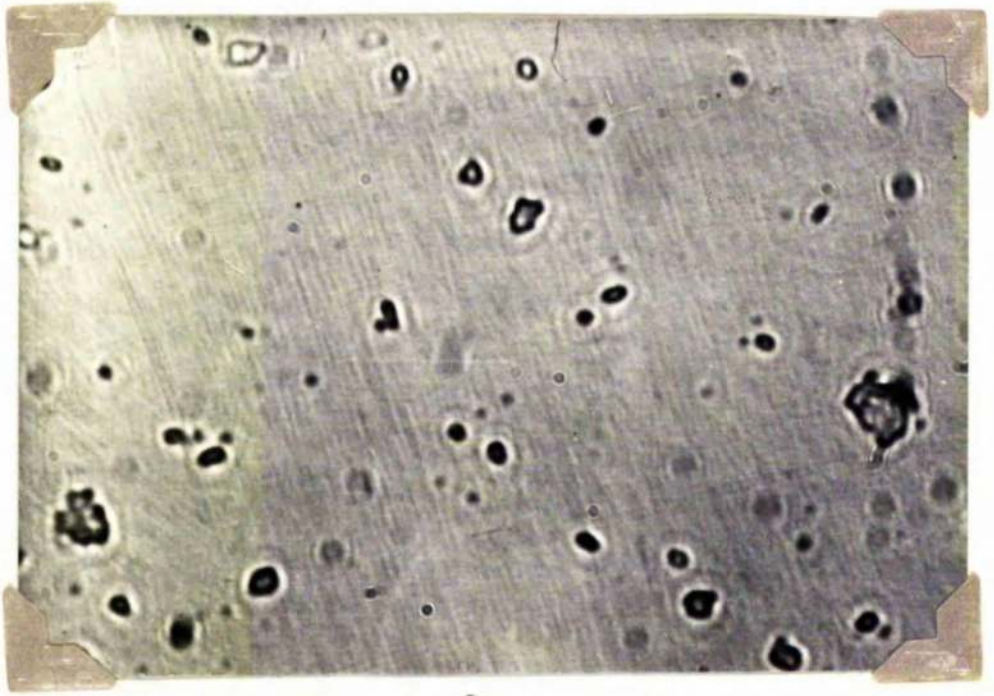

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SECTION 5

Effect of Aqueous Sprays on the Size Distribution of Airborne Dusts

The effect of water and aqueous solutions of surface-active agents on the concentrations of airborne dust was dealt with in Sections 3 and 4. Information, however, on the size distribution of such dust clouds before and after spraying must also be made available.

The dust samples taken by Thermal Precipitator and used to estimate the dust cloud concentration were now utilised to determine the size distribution of the dust in suspension. To construct a suitable size distribution curve at least 400 particles were counted and sized. As no significant convection currents existed in the chamber the sample taken at the centre of the chamber was considered to be representative of the dust cloud.

Variation of Size Distribution with Time

It has already been shown that after 90 minutes of aggregation conditions in the dust cloud were virtually constant and the dust concentration was found to alter very slowly over the next few hours. The reproducibility of the clouds (coal dust, silica dust and fly ash) in respect of concentration and size distribution has also been shown (Section 3, Tables 17 and 16) to be good. They were also found to agree well with natural airborne coal dust and a mixed rock and coal dust cloud

sampled underground in respect of particle and distribution.

The variation of the size distribution of the dust particles with time for coal dust was followed using the slides obtained in the work relating cloud concentration and time. Results are given in Table 58 and shown in histogram form in Fig. 29.

They show that the size distribution alters very little after the first 90 minutes, the only change being in the dust of large particle size which naturally tends to settle. The dramatic change in size distribution over the first 90 minutes can be seen in comparing Figs. 30a and 30b which show the coal dust cloud immediately on formation, with a number of aggregates visible, and the same cloud 90 minutes later when few aggregates are to be seen.

This variation of size distribution with time is typical. The view that the larger particles settle out more quickly is supported by the fact that 96 per cent of the dust particles are less than 2 microns after 8 hours. This effect is masked at the higher dust concentrations by the aggregation of the smaller particles to form larger ones giving little variation in the size distribution curves over the first 8 hours.

Aggregation to a certain degree can be seen to take place by noting the larger size ranges in Fig. 29. On formation it can be seen that quite a few aggregates are present but after

Table 58

Coal Dust

Percentage Number of Particles

Size Microns	Immediately On Formation	After 1 hr.	After 2 hrs.	After 4 hrs.	After 6 hrs.	After 8 hrs.
0.2 - 0.4	10.5	9.2	11.6	11.4	12.1	12.0
0.4 - 0.8	22.7	18.9	22.9	21.6	22.5	22.6
0.8 - 1.2	26.3	23.8	24.1	23.4	22.4	21.9
1.2 - 1.6	21.5	15.9	15.9	16.2	17.3	18.5
1.6 - 2.0	14.2	14.0	8.6	10.7	11.2	10.9
2.0 - 2.5	4.2	9.1	7.4	8.5	9.1	9.0
2.5 - 3.0	0.5	1.9	2.3	2.4	1.8	2.0
3.0 - 4.0	0.1	2.5	1.8	2.1	2.2	2.1
4.0 - 5.0	-	2.3	2.0	1.9	0.8	0.6
5	-	2.4	2.4	1.8	0.6	0.4
	100.0	100.0	100.0	100.0	100.0	100.0

FIGURE 29.

SIZE DISTRIBUTION OF COAL DUST AT DIFFERENT SEDIMENTATION TIMES

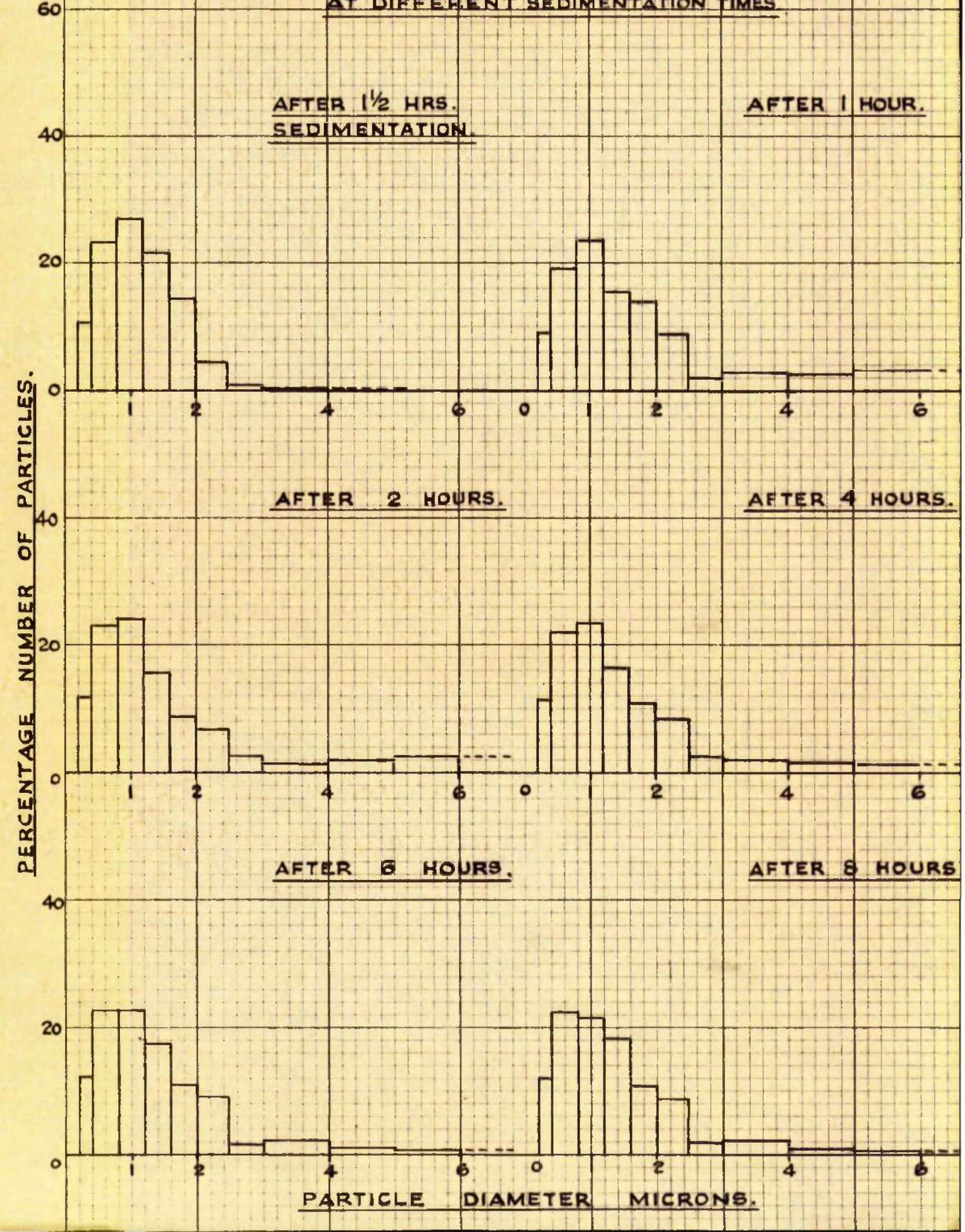
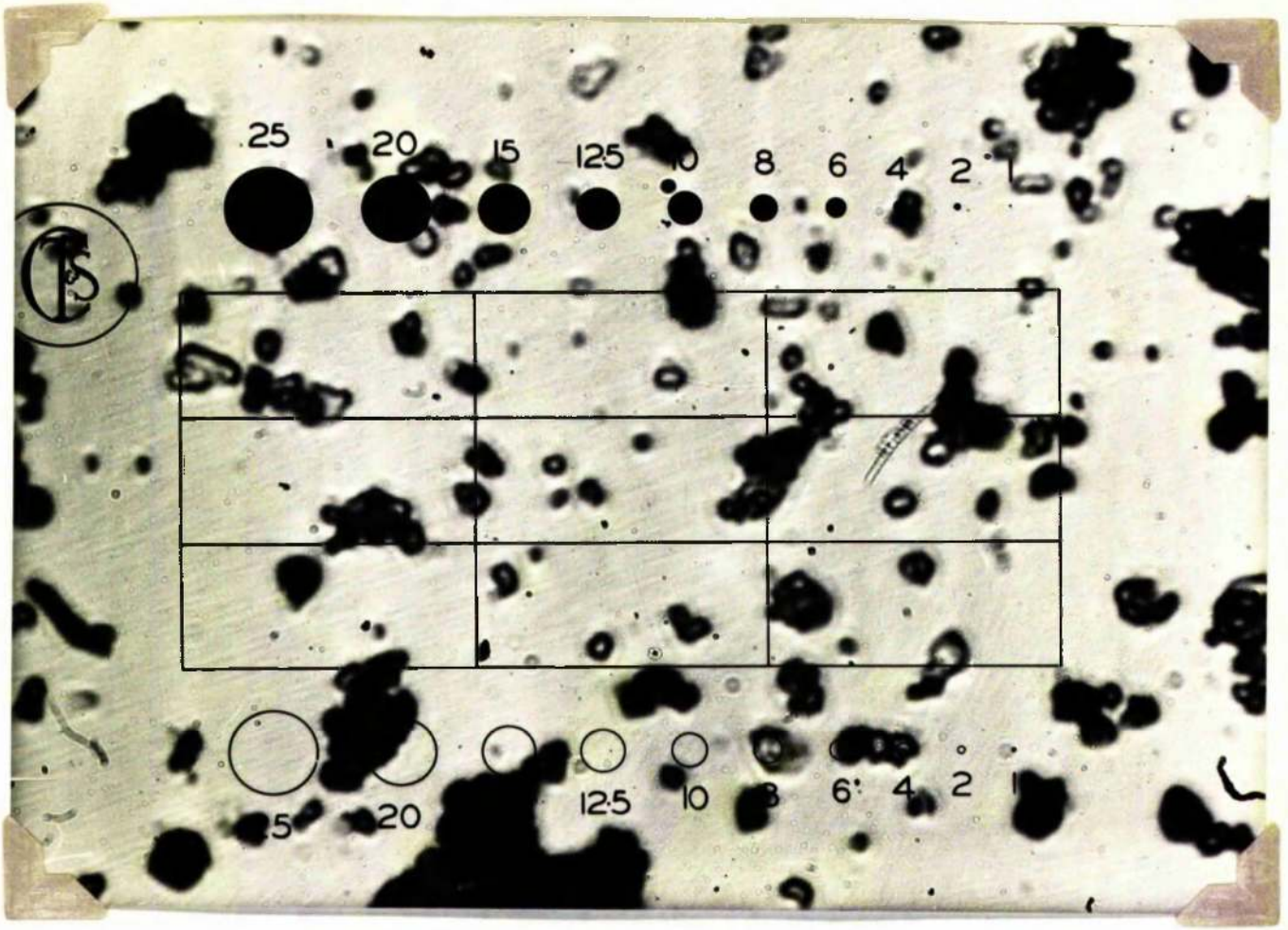


FIGURE 30



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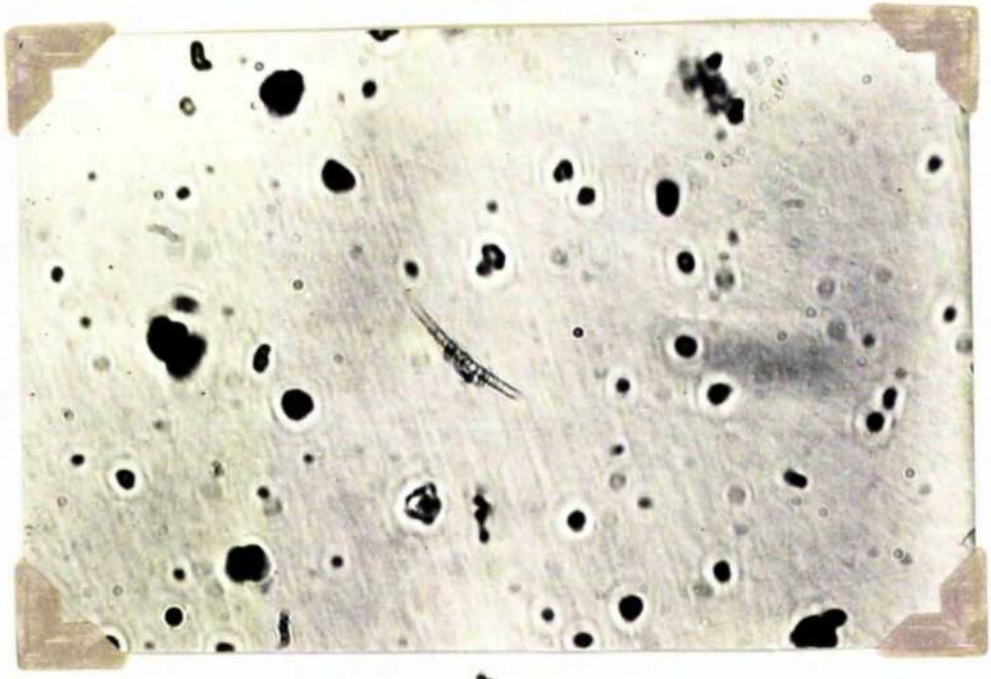


b

90 minutes the histogram is quite compact indicating that very little aggregation is taking place. During the next few hours the larger sizes begin to appear again indicating some aggregation of small particles to form large aggregates.

The decrease in the number of particles in suspension in the chamber is therefore due to two factors :

(a) aggregation of the small particles to form large aggregates

(b) sedimentation of the larger aggregates from suspension.

Most of the particles, being surrounded by a layer of air, failed to strike the walls of the chamber during sedimentation.

Effect of Spraying on the Size Distribution

Coal dust clouds which had been allowed to settle for 90 minutes were sprayed for 1 minute with water at 30, 60, 100 and 150 lb./in.^{2}. Samples of the dust before and after spraying were taken for evaluation. The size distributions obtained are shown in Table 59 and in histogram form in Fig. 31.

They show that the larger dust and aggregates were preferentially removed and that more of the dust of large particle size, >1 micron, was removed the higher the spray pressure employed. Even at 150 lb./in^2. however, most of the dust <1 micron in diameter remained in suspension.

Removal of the larger dust particles will be due to their

Table 59

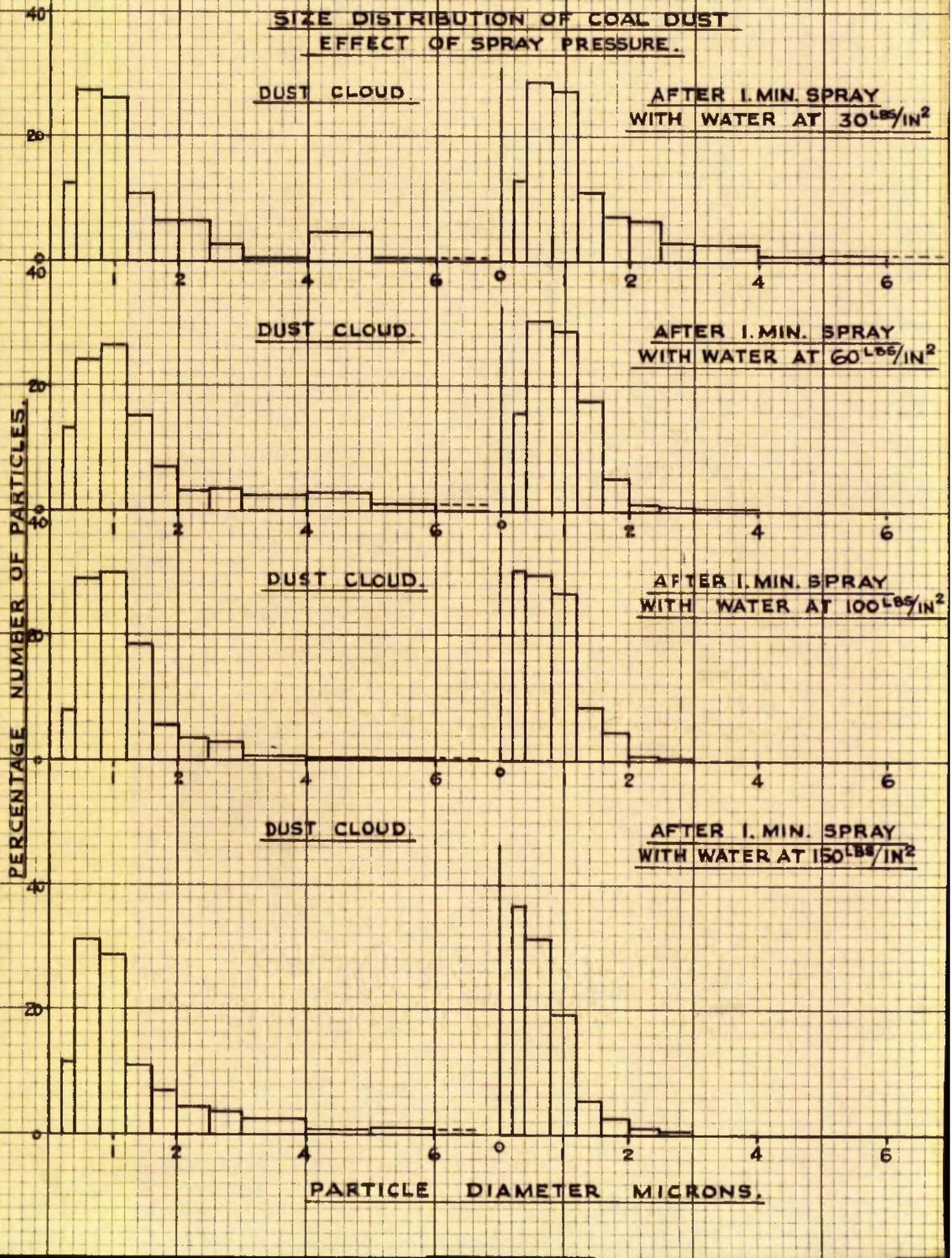
Coal Dust

Percentage Number of Particles

Size Microns	Before Spray	After 1 min. at 30 lb./in²	Before Spray	After 1 min. at 60 lb./in²	Before Spray	After 1 min. at 100 lb./in²	Before Spray	After 1 min. at 150 lb./in²
0.2 -0.4	12.6	12.6	13.4	15.7	8.0	30.1	11.6	38.4
0.4 -0.8	27.7	28.3	24.1	30.4	29.1	29.5	30.7	33.6
0.8 -1.2	26.1	27.4	26.5	28.6	30.0	26.3	28.3	18.3
1.2 -1.6	11.0	10.8	15.0	17.5	18.4	8.3	11.5	5.8
1.6 -2.0	6.5	7.3	7.4	5.4	5.8	4.2	6.4	2.5
2.0 -2.5	6.8	6.2	3.6	1.4	3.9	0.9	4.2	1.0
2.5 -3.0	3.2	2.9	3.8	0.6	3.4	0.6	3.8	0.4
3.0 -4.0	0.8	2.6	2.3	0.4	0.6	-	2.4	-
4.0- 5.0	4.9	0.9	2.8	-	0.5	-	0.5	-
5	0.7	1.0	1.1	-	0.3	-	0.6	-
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

FIGURE 31.

SIZE DISTRIBUTION OF COAL DUST
EFFECT OF SPRAY PRESSURE.



inertia which increases their chance of coming into contact with a water droplet and the fact that some of the aggregates are broken up into smaller particles by the water droplets or by the turbulence caused by the spray. Although none of these factors can be said to be predominant, they all obviously play a part.

Increase in spray pressure alters the three main characteristics of the spray, viz :

(a) liquid throughput

(b) average droplet size

(c) droplet velocity

Each of these has an effect on the amount of dust knocked down and on the particle size of the dust removed. In the design of an effective spray system it is therefore necessary to know the effect of each on the particle size of the dust removed.

Effect of Altering Spray Throughput

These runs were carried out using nozzle A and spraying for 30 seconds, 2 minutes and 10 minutes with water at 60 lb./in^2. Under these conditions the average droplet size was kept constant at 53 microns and the droplet velocity remained steady, the only variable being the liquid throughput.

The results obtained for coal dust and silica dust are given in Tables 60 and 61 and are shown in histogram form in

Table 60

Coal Dust

Percentage Number of Particles

Size Microns	Before Spray	After 30 sec, at 60 lb./in.^{2}	After 2 mins, at 60 lb./in.^{2}	After 10 mins. at 60 lb./in.^{2}
0.2 - 0.4	8.3	11.6	21.1	62.6
0.4 - 0.8	19.0	23.0	32.3	29.4
0.8 - 1.2	23.8	24.1	25.6	4.3
1.2 - 1.6	15.9	15.6	7.6	1.3
1.6 - 2.0	14.0	8.7	6.9	1.1
2.0 - 2.5	9.2	7.6	3.7	1.3
2.5 - 3.0	2.8	5.4	1.4	-
3.0 - 4.0	2.3	1.6	0.7	-
4.0 - 5.0	2.3	1.6	-	-
5	2.4	0.8	0.7	-
	100.0	100.0	100.0	100.0

Table 61

Silica Dust

Percentage Number of Particles

Size Microns	Before Spray	After 30 sec. at 60lb./in.^{2}	After 2 mins. at 60lb./in.^{2}	After 10 mins. at 60lb./in.^{2}
0.2 - 0.4	8.4	11.4	30.3	40.2
0.4 - 0.8	28.9	29.4	39.1	34.5
0.8 - 1.2	30.0	23.7	21.5	18.8
1.2 -1.6	19.1	16.2	7.2	5.3
1.6 - 2.0	5.1	9.3	1.2	1.1
2.0 - 2.5	3.4	5.1	0.7	-
2.5 - 3.0	3.9	2.8	-	-
3.0 - 4.0	0.8	1.2	-	0.1
4.0 - 5.0	0.4	0.8	-	-
5	-	0.1	-	-
	100.0	100.0	100.0	100.0

Figs. 32 and 33. Little change is to be observed in the size distributions obtained over the first 2 minutes of spraying but after 10 minutes 99 per cent of the dust remaining in suspension is ≤ 2 microns, the larger dust having again been preferentially removed.

From these results it appears that increase in throughput alone is sufficient to give a certain reduction in the dust of small particle size. Considering the system theoretically, the same volume of water is being atomised per unit of time into the same number of droplets of the same size range. Each small dust particle which escapes "knockdown" by being swept aside will therefore be again swept aside by the next wave of droplets. The longer the duration of the spray period, however, the greater is the possibility of the wettable dust coming into contact with a droplet and being carried down. There will also be some small "knockdown" of the very small dust which in the turbulent air created will collide and aggregate with other small dust particles to be carried down. Increase of throughput at any one pressure can only give a limited increase in "knockdown" although 10 minutes spray with water at 60 lb./in^2. has a very much greater effect than allowing the dust to settle naturally under gravity for 8 hours.

FIGURE 32.

SIZE DISTRIBUTION OF COAL DUST. EFFECT OF SPRAY THROUGHPUT.

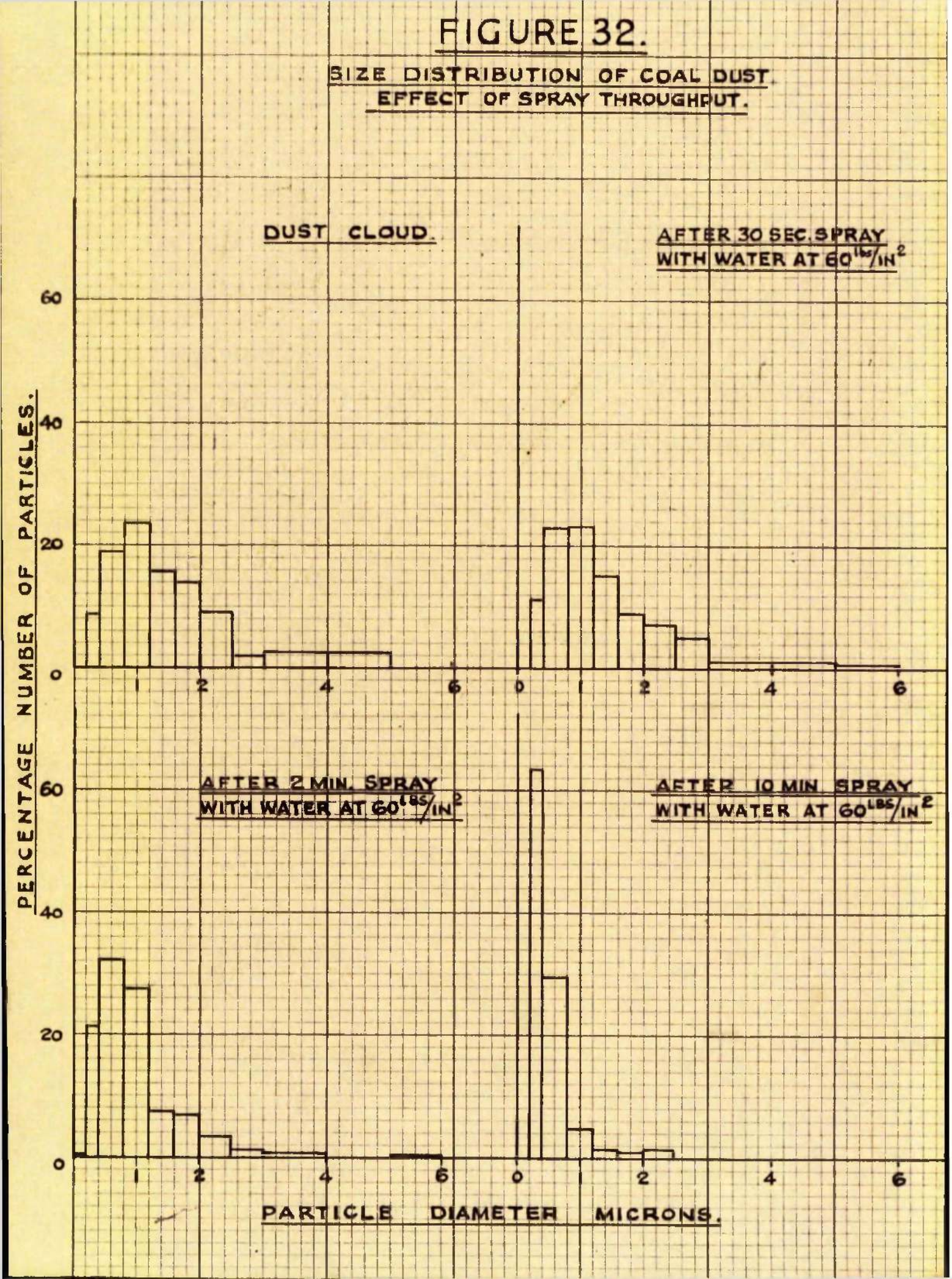
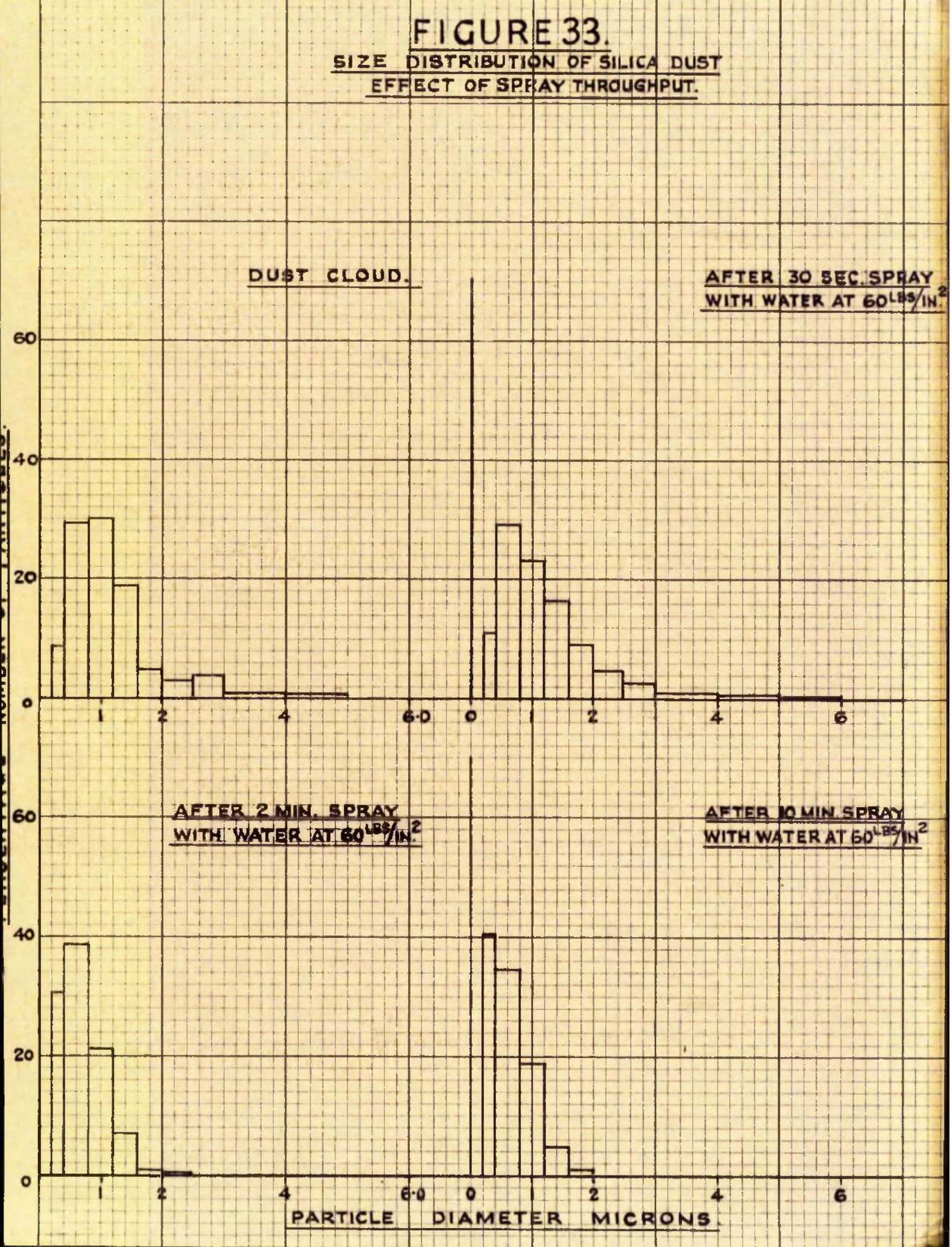


FIGURE 33.

SIZE DISTRIBUTION OF SILICA DUST
EFFECT OF SPRAY THROUGHPUT.



Effect of Average Droplet Size

Results obtained by Sell and Davies (125, 126) show that substantial improvement can be achieved in gravity scrubbers by utilising spray droplets of the correct size. It was therefore necessary to include the effect of droplet size in this investigation.

As shown in Section 3, the reduction in dust concentration was greater the smaller the droplet size. However, the larger the droplet size employed the better was the effectiveness measured in particles per droplet.

Table 62 and Fig. 34 show the values obtained for the size distribution of coal dust clouds before and after spray runs under the conditions given in Table 21, the throughput and velocity being constant. From them it would appear that the coarsest spray (average droplet size 96 microns) removed slightly more of the smaller dust particles in the cloud than the finer sprays. Even using this coarse spray most of the dust < 1 micron in size still remained in suspension. These results would indicate that an optimum droplet size greater than 96 microns exists for these dusts which would remove more of the dangerous size without altering the droplet velocity or the throughput.

Here again the reduction obtained is much greater than

Table 62

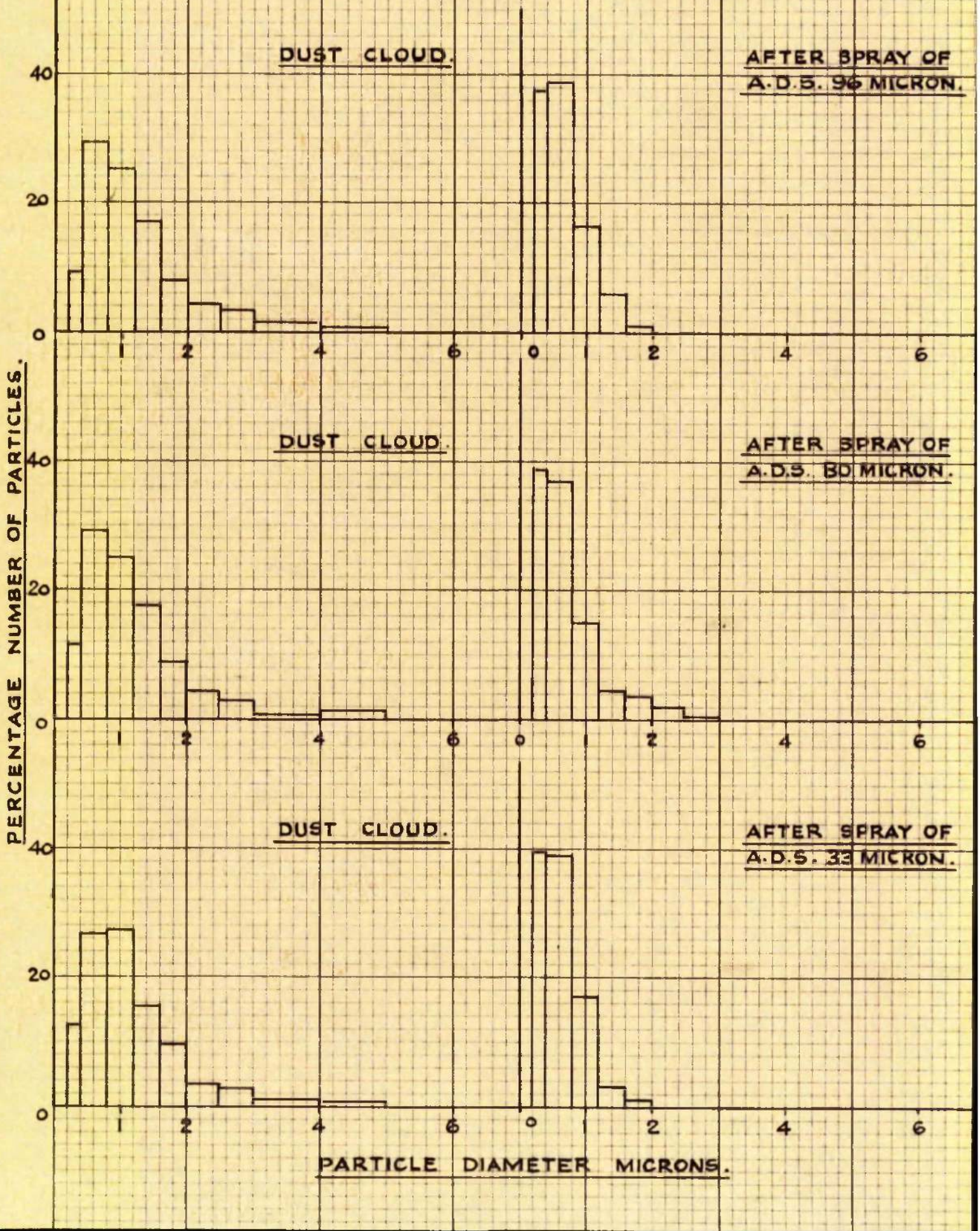
Coal Dust

Percentage Number of Particles

Size Microns	Before Spray	After Spray of A.D.S.96micron	Before Spray	After Spray of A.D.S.80micron	Before Spray	After Spray of A.D.S.33micron
0.2 - 0.4	9.7	37.5	10.6	38.3	12.3	39.6
0.4 - 0.8	29.3	39.0	29.0	37.1	26.5	38.5
0.8 - 1.2	25.5	16.3	25.0	14.6	27.3	17.1
1.2 - 1.6	17.1	6.0	17.8	4.2	15.5	3.6
1.6 - 2.0	8.0	1.2	8.8	3.7	9.6	1.2
2.0 - 2.5	4.2	-	4.1	2.0	3.7	-
2.5 - 3.0	3.7	-	2.6	0.1	3.0	-
3.0 - 4.0	1.6	-	0.8	-	1.2	-
4.0 - 5.0	0.9	-	1.3	-	0.9	-
5	-	-	-	-	-	-
	100.0	100.0	100.0	100.0	100.0	100.0

FIGURE 34.

SIZE DISTRIBUTION OF COAL DUST
EFFECT OF AVERAGE DROPLET SIZE.



that got under natural sedimentation over a long period.

Effect of Droplet Velocity

Results obtained by spraying coal dust clouds with droplets of different velocities under the conditions given in Table 22 are shown in histogram form in Fig. 35 and tabulated in Table 63.

From the histpgrams it is not obvious what effect increase in droplet velocity has on the size distribution of the clouds. This agrees with the effect of droplet velocity on cloud concentration reported in Section 3. This lack of difference may, as has been said before, be due to the narrow range of velocity investigated. If the droplet velocity is increased sufficiently some improvement should be obtained though air movement would inevitably push aside some small particles.

FIGURE 35.

SIZE DISTRIBUTION OF COAL DUST
EFFECT OF DROPLET VELOCITY

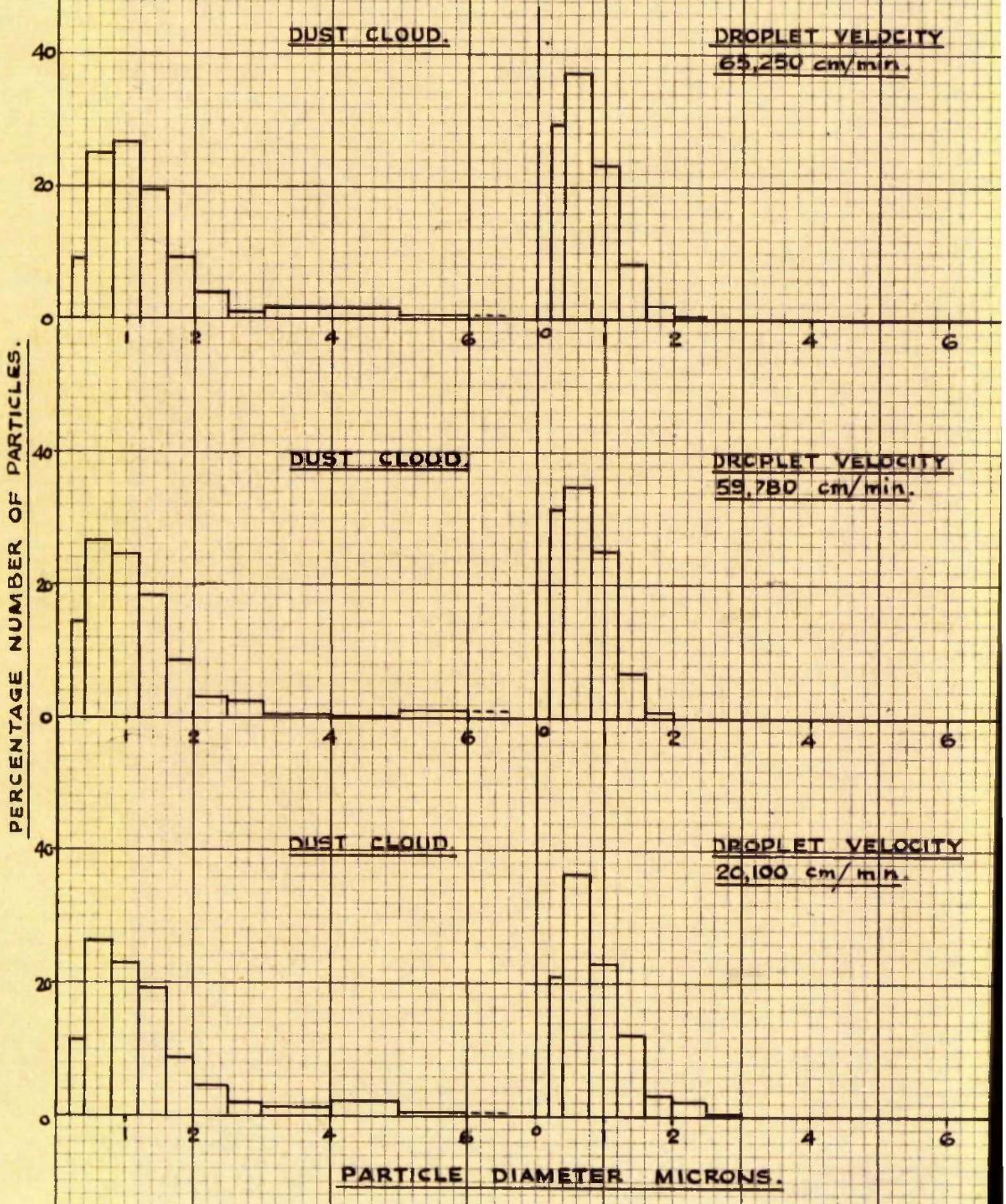


Table 63

Coal Dust

Percentage Number of Particles

Size Microns	Before Spray	After Spray of Velocity 65 250 cm./min.	Before Spray	After Spray of Velocity 59 780 cm./min.	Before Spray	After Spray of Velocity 20,100cm/min
0.2 - 0.4	9.3	29.5	14.2	31.6	11.7	21.4
0.4 - 0.8	25.4	37.3	26.3	34.9	26.1	36.6
0.8 - 1.2	26.7	22.7	24.2	25.3	23.4	23.6
1.2 - 1.6	19.6	8.2	18.1	7.1	19.4	12.5
1.6 - 2.0	9.3	2.0	8.7	1.1	8.5	3.4
2.0 - 2.5	4.0	0.3	3.4	-	4.5	2.7
2.5 - 3.0	1.3	-	2.6	-	2.0	0.3
3.0 - 4.0	1.9	-	0.8	-	1.6	-
4.0 - 5.0	1.9	-	0.6	-	2.1	-
5	0.6	-	1.1	-	0.7	-
	100.0	100.0	100.0	100.0	100.0	100.0

SECTION 6

Effect of Surface-Active Agents on the Size Distribution of Airborne Dusts

It was shown in Section 2 that at high spray pressures the use of aqueous solutions of low surface tension resulted in no improvement in liquid atomisation. The "knockdown" of dust using such solutions as shown in Section 4 was similar to that obtained using water. At low spray pressures where the effect of surface tension on average droplet size was more apparent there was no indication as to which liquid was the most effective.

Although the use of solutions of low surface tension had little effect on the amount of dust suppressed their effect on the size distribution of the airborne dusts was of great interest. One of these aqueous solutions might, because of some property, be more effective in removing the smaller, most dangerous size fraction.

Effect of Aqueous Solutions of Low Surface Tension at High Pressures

Size analyses were carried out on the slides obtained for the investigation of the effect of spraying low surface tension solutions, sodium oleate, iso-butyl alcohol and K-PE, on coal dust and silica dust.

The results including those for water sprays are given in

Tables 64 and 65 and shown in Figs. 36 and 37. It can be seen that no improvement over water is to be achieved by employing such solutions at this pressure. Of these aqueous solutions iso-butyl alcohol is the least effective in respect of coal dust.

Effect of Aqueous Solutions of Low Surface Tension at Low Pressure

Silica dust clouds were sprayed with an aqueous solution of sodium oleate and water for 1 minute at 30 lb./in^2. and the results are compared in Table 66 and Fig. 38 with those for sodium oleate at 60 lb./in^2.

It can be seen that reduction of the spray pressure from 60 to 30 lb/in^2., giving an increase in average droplet size from 53 to 78 microns and a reduction in droplet velocity, has made little difference to the size distribution of the dust remaining. Aqueous sodium oleate has already been shown, Section 4, to give the same reduction in concentration at 60 and 30 lb./in^2. It would appear that the combined effects of increase in droplet size, decrease in droplet velocity and in volume of solution sprayed balanced out. This was also shown in Table 59 and Fig. 31 to be the case for coal dust sprayed with water. Surface tension had then no noticeable effect.

Table 6b

Coal Dust

Percentage Number of Particles

Size Microns	Before Spray	After 1 min. with K-PE at 60 lb/in^2	Before Spray	After 1 min. with iso-butyl alcohol at 60 lb/in.^{2}	Before Spray	After 1 min with water at 60lb/in^2
0.2 - 0.4	9.3	20.5	7.3	18.6	13.4	15.7
0.4 - 0.8	16.7	29.3	25.7	22.2	24.1	30.4
0.8 - 1.2	19.5	26.9	25.3	21.0	26.5	28.6
1.2 - 1.6	18.1	6.5	16.0	17.0	15.0	17.5
1.6 - 2.0	14.3	5.2	10.9	8.8	7.4	5.4
2.0 - 2.5	7.2	5.6	5.7	4.8	3.6	1.4
2.5 - 3.0	6.1	2.3	-	0.5	3.8	0.6
3.0 - 4.0	3.9	1.3	4.0	1.9	2.3	0.4
4.0 - 5.0	3.0	2.4	1.8	1.8	2.8	-
5	1.9	-	3.3	3.4	1.1	-
	100.0	100.0	100.0	100.0	100.0	100.0

Table 65

Silica Dust

Percentage Number of Particles

Size Microns	Before Spray	After 1 min. with Sodium Oleate at 60 lb./in.^{2}	Before Spray	After 1 min. with iso-Butyl Alcohol at 60 lb./in.^{2}	Before Spray	After 1 min. with water at 60lb/in.^{2}
0.2 - 0.4	8.5	24.2	11.6	24.8	12.5	25.1
0.4 - 0.8	23.8	28.2	24.2	29.3	29.3	30.3
0.8 - 1.2	25.2	23.4	22.7	20.2	29.6	18.6
1.2 - 1.6	15.0	11.8	17.2	13.7	13.2	15.2
1.6 - 2.0	11.9	6.1	9.5	8.6	5.5	7.1
2.0 - 2.5	6.6	4.3	8.2	3.2	1.8	0.2
2.5 - 3.0	3.1	0.8	4.1	0.2	2.4	1.8
3.0 - 4.0	3.9	0.7	1.4	-	1.7	1.7
4.0 - 5.0	2.0	0.4	0.4	-	2.4	-
5	-	0.1	0.7	-	1.6	-
	100.0	100.0	100.0	100.0	100.0	100.0

FIGURE 36.

SIZE DISTRIBUTION OF COAL DUST
EFFECT OF LOW SURFACE TENSION SOLUTIONS
AT HIGH PRESSURE.

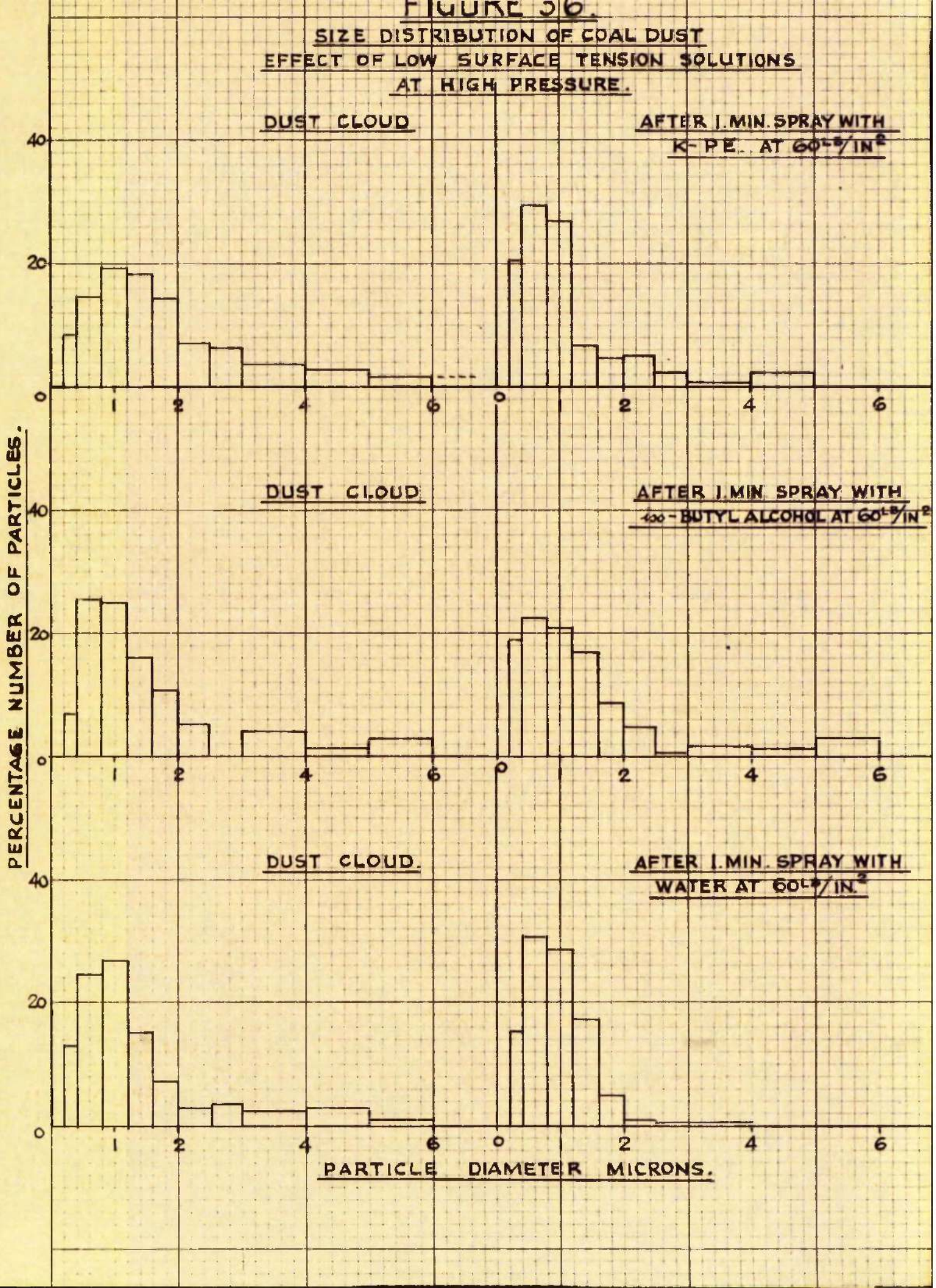


FIGURE 37.

SIZE DISTRIBUTION OF SILICA DUST
EFFECT OF LOW SURFACE TENSION SOLUTIONS
AT HIGH PRESSURE.

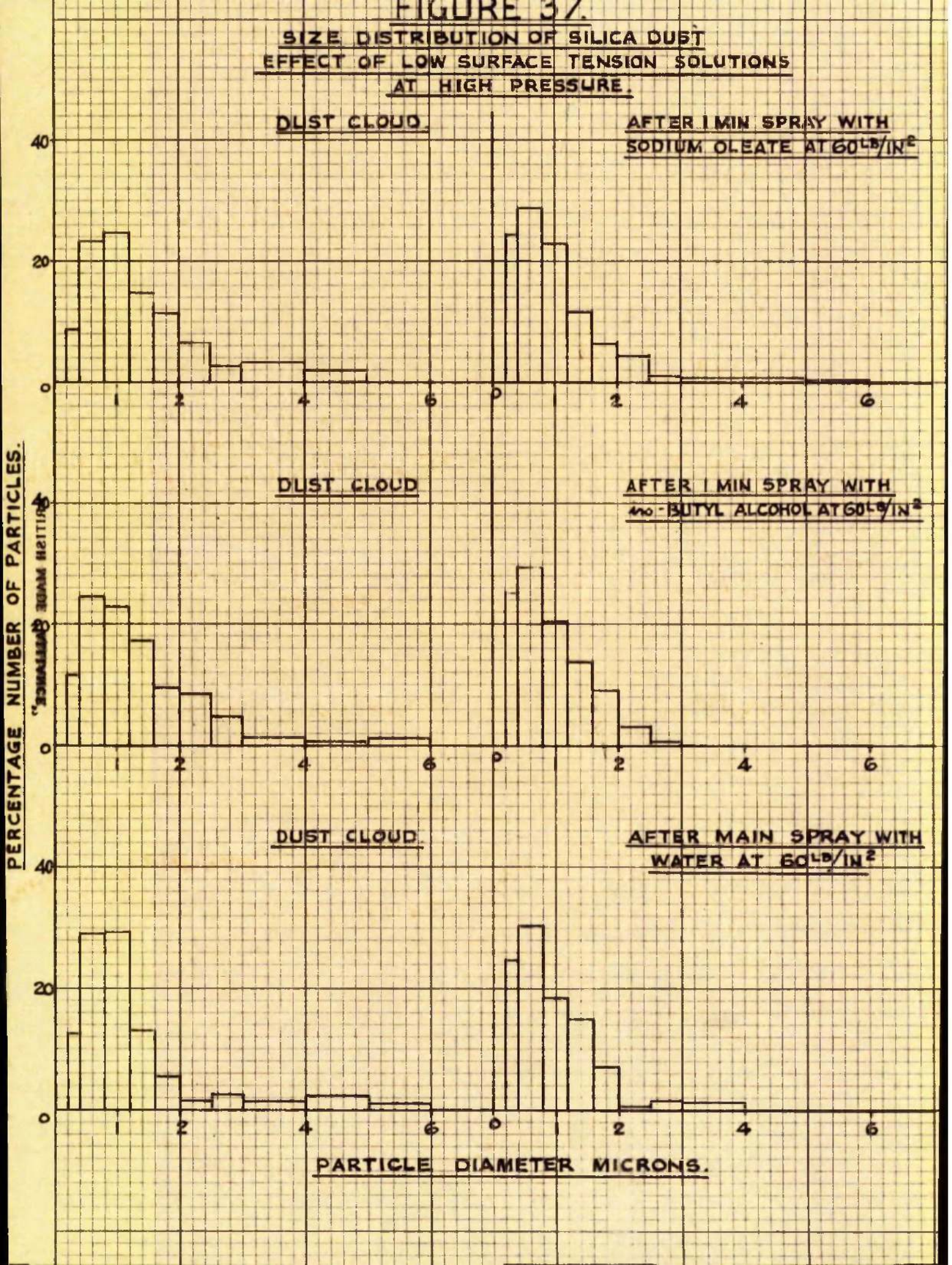


Table 66

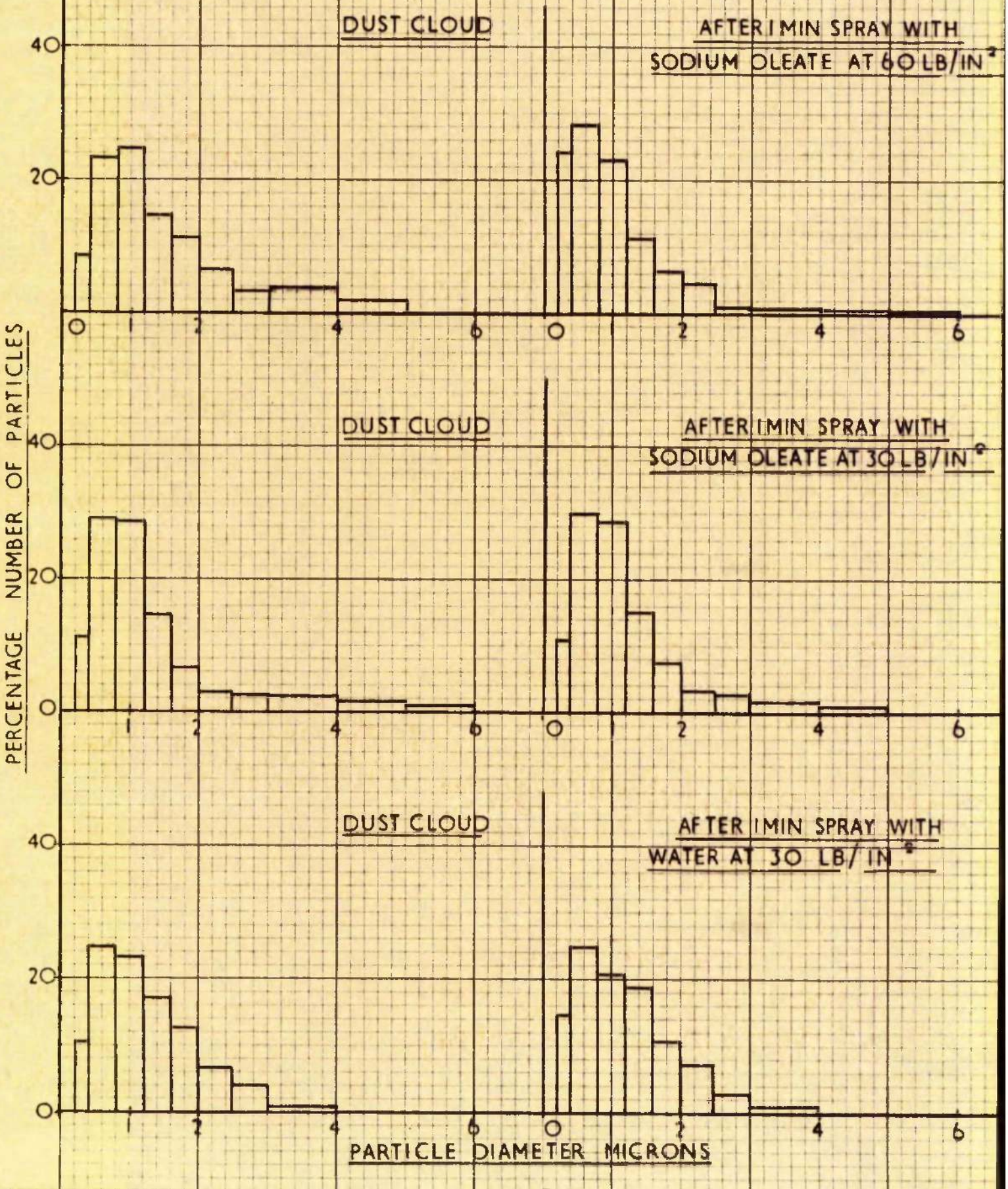
Silica Dust

Percentage Number of Particles

Size Microns	Before Spray	After 1min. with sodium oleate at 60 lb./in^2.	Before Spray	After 1min. with sodium oleate at 30 lb/in^2.	Before Spray	After 1min. with water at 30 lb/in.^{2}
0.2 - 0.4	8.5	24.2	11.3	10.6	10.4	14.2
0.4 - 0.8	23.8	28.2	29.1	29.9	25.2	25.1
0.8 - 1.2	25.2	23.4	28.7	28.4	23.6	20.6
1.2 - 1.6	15.0	11.8	14.6	15.2	17.1	18.4
1.6 - 2.0	11.9	6.1	6.2	7.6	12.3	10.3
2.0 - 2.5	6.6	4.3	2.8	3.4	6.5	7.5
2.5 - 3.0	3.1	0.8	2.4	2.6	4.0	3.0
3.0 - 4.0	3.9	0.7	2.2	1.9	0.9	0.9
4.0 - 5.0	2.0	0.4	1.7	0.4	-	-
5	-	0.1	1.0	-	-	-
	100.0	100.0	100.0	100.0	100.0	100.0

FIGURE 38

SIZE DISTRIBUTION OF SILICA DUST
EFFECT OF LOW SURFACE TENSION SOLUTIONS
AT LOW PRESSURE.



Effect of cycloHexane Sprays on Coal Dust

The anomalous effect of cycloHexane on reduction in dust concentration has been discussed in Section 4. Table 67 gives the size distributions of coal dust clouds before and after spraying with cycloHexane at 60 and 30 lb./in.^{2} They are also shown in histogram form in Fig. 39.

They demonstrate that cycloHexane enables more dust in the intermediate range 1 - 2.5 microns to be removed. Reduction of the spray pressure has no apparent effect on the size of the dust removed.

The photographs shown in Section 5 were obtained from a representative portion of the slide projected onto the screen of the Vickers Projection Microscope.

Table 67

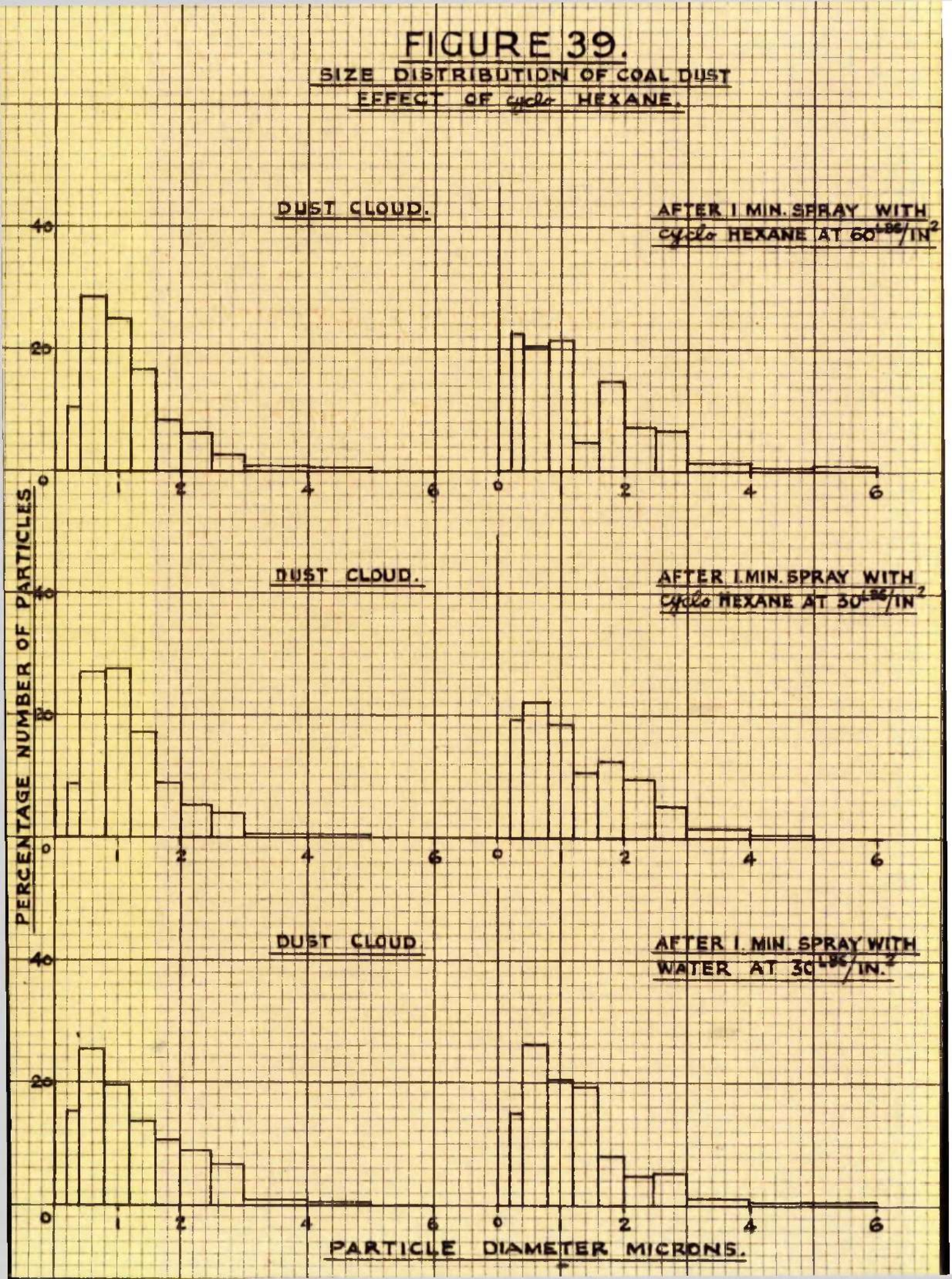
Coal Dust

Percentage Number of Particles

Size Microns	Before Spray	After 1 min. with cyclohexane at 60lb/in.^{2}	Before Spray	After 1 min. with cyclohexane at 30lb/in.^{2}	Before Spray	After 1 min with water at at 30lb/in.^{2}
0.2 - 0.4	10.4	22.1	8.6	19.8	15.1	14.6
0.4 - 0.8	28.2	20.2	27.2	22.1	25.6	26.1
0.8 - 1.2	25.1	21.5	27.6	18.7	19.7	20.2
1.2 - 1.6	16.6	5.0	17.3	10.2	13.5	19.4
1.6 - 2.0	8.2	14.6	9.1	12.1	10.2	8.0
2.5 - 3.0	3.3	6.8	4.0	5.2	6.2	5.2
3.0 - 4.0	0.9	1.6	0.3	1.7	0.6	1.4
4.0 - 5.0	0.6	0.2	0.4	0.3	0.4	0.2
5	-	0.4	-	-	-	0.1
	100.0	100.0	100.0	100.0	100.0	100.0

FIGURE 39.

SIZE DISTRIBUTION OF COAL DUST
EFFECT OF *cyclo* HEXANE.



APPENDIX

The Design of an Airborne Dust Sampler

Introduction

This section of the work was begun with the object of designing a bulk sampler for airborne coal dust. Many instruments exist, most of which enable a snap sample, suitable only for microscopic examination, to be taken. For chemical analysis a much larger sample(ca 5 gm.) obtained by a long period sampler would be required.

Dust Clouds

The dust cloud concentration at the coal face is extremely variable. In roadways immediately outby the working face, where the air velocity is much lower, the concentration is much more uniform. These velocities are such that particles >1 micron in size may be carried along for quite a distance.

However, the incidence of disease is highest among face workers, indicating that the injurious dust is breathed mainly at the working face.

In practice, the factors which influence the amount of dust produced are :

(a) the nature of the coal worked

(b) whether worked by hand, cutter or pneumatic pick

(c) size, type and condition of conveyors used

(d) intensity of mining operation such as rate of loading coal and speed of working conveyors

(e) changes in velocity and quantity of air circulating.

Although many of these factors may vary throughout a shift it is found that fairly long periods occur when (a), (b) and (c) are almost constant and that variations in the resulting dust concentration are of a small order (136).

Sampling Methods

Of the sampling methods which have been devised most are either inaccurate, complicated or inapplicable to underground conditions.

For use in mines, the sampling apparatus should be robust, simple light in weight and capable of running unattended for long periods. The collection of the sample should involve no elaborate technique.

The size of sample required indicated that a quantitative rather than a qualitative method should be employed. Thus the dust cloud was passed through a suitable filter which removed the dust, allowing the clean air to pass on. A source of suction was required. This type of sampler has been used by several workers (136, 137).

The Soxhlet thimble type of filter was used as it appeared to be very satisfactory.

Factors Affecting Sampling

From investigations carried out by previous workers it has been shown that a true sample of airborne dust can be obtained if the sampling velocity is the same as that of the air stream in the roadway. This has been confirmed by investigators here (136,138) and in the United States (139).

If the sampling velocity is greater than the air speed the flow lines gather together into the orifice and heavier particles tend to shoot straight on, escaping collection, unless they happen to be in direct line with the orifice.

However, if the sampling velocity is less than the air speed the stream lines expand into the orifice with the risk of collecting too many large particles. For accurate sampling, orifices facing upstream should have a sharp leading edge and should sample at velocities as close as possible to that of the air-stream. This is called " Isokinetic Sampling "

Using a sharp-edged tube facing upstream the following formula will give an estimate of the sampling error due to departure from isokinetic conditions.

$$C_s/C_a = V_a/V_s = \tfrac{1}{2}\,(\,V_a/V_s - 1\,)/(P + \tfrac{1}{2})$$

C_s/C_a is the ratio of the concentration of dust in the sample to the airborne dust concentration.

V_a/V_s is the ratio of the air speed to the sampling speed.

P is the particle parameter, a measure of the effective size of the particles.

$$P = d^2\rho\, V_a/9\eta D$$

d = particle diameter

ρ = density of particle

η = viscosity of air

D = orifice diameter

P is dimensionless and as long as the velocity ratio is between $\frac{1}{2}$ and 2 the concentration error is less than 20 per cent for values of P below 0.1. A large diameter for the sampling tube helps to keep P small.

It is usually possible to neglect sample orifice errors when the particles are small enough to make P less than 0.1.

Apparatus

Since compressed air is a common source of energy in coal mines, working pressure being about 60 lb./in^2., the suction was produced by an air ejector (140) of orifice diameter 2.1 mm. Connections were of hosepipe and a reducing valve between the compressed air supply and the ejector controlled the flow rate.

The dust cloud was drawn through a 1.1 in. diameter orifice filter, clean air passing on to a flow meter of the dry-bellows type (141) capable of recording a flow rate of <u>ca</u> 300 ft^3/hr.

The arrangement of the apparatus is shown in Fig. 40.

Trials

Figures shown in Table 68 give the suction obtained at different air pressures. The corresponding rates of air flow through the filter are also given.

When sampling isokinetically at a rate of 0.7 ft.^{3}/min. with the above apparatus, at the coal face, in a dust cloud of approximately 290 particles per cubic centimetre, only 50 mg. of dust was obtained for an 8 hour run. This showed that isokinetic sampling would not give the weight of dust required in a reasonable time. It was obvious, therefore, that the only means by which a larger sample could be conveniently collected would be to increase the sampling rate. To achieve this while maintaining isokinetic sampling an increased diameter of sampling orifice was obviously required.

It was decided to investigate the sampling accuracy of orifices of varying diameter, using a thermal precipitator to evaluate the dust clouds.

Apparatus

The dust chamber described in Section 3 was used in this work. A roughly constant dust cloud was obtained by drawing the dust up from a cylindrical glass vessel and injecting it into the top of the chamber by means of an injector. This dust injected at

FIGURE 40

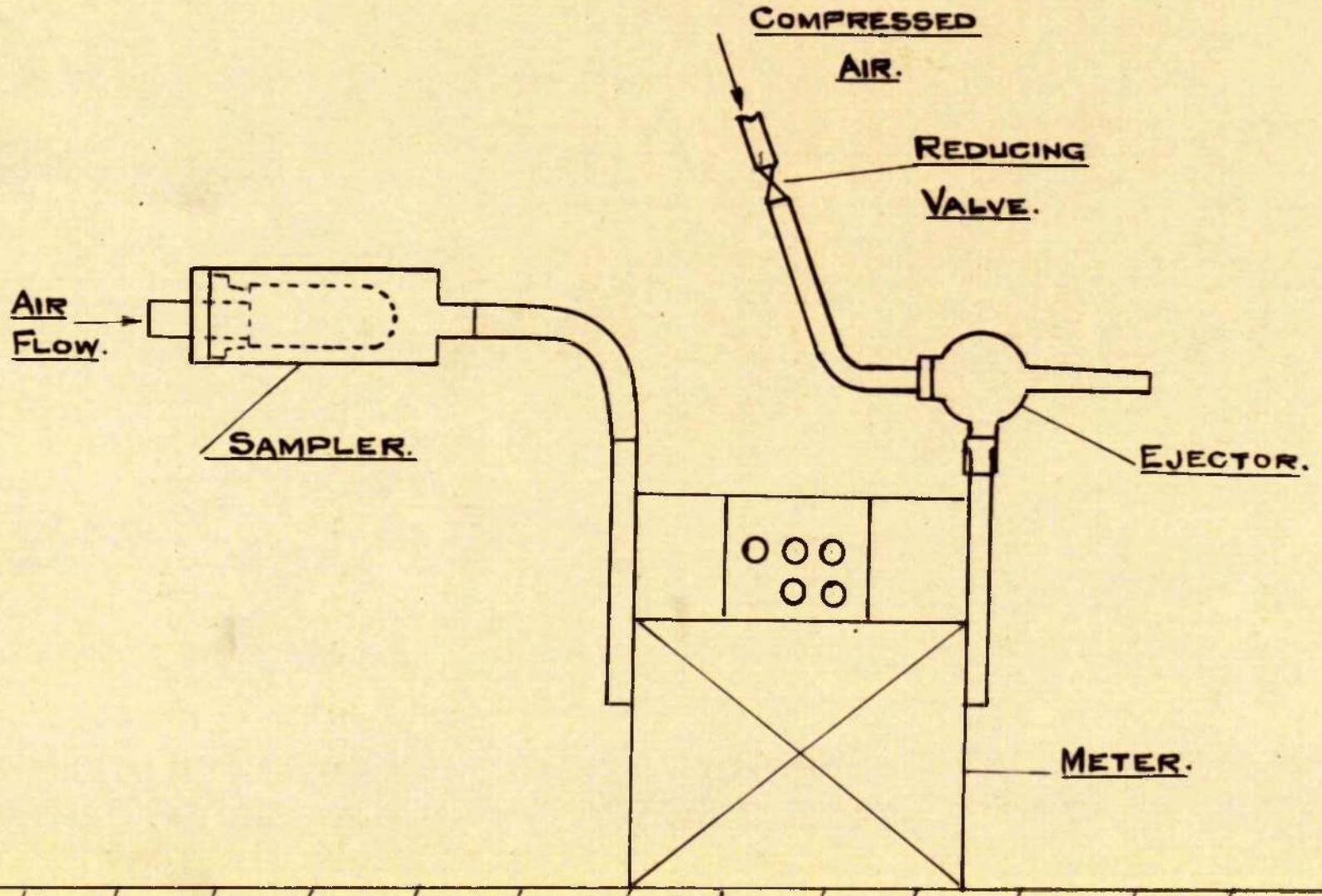

COMPRESSED
AIR.
REDUCING
VALVE.
AIR
FLOW.
SAMPLER.
EJECTOR.
METER.

Table 68

Compressed Air Pressure, lb./in.^{2}	Suction cm. Water Gauge	Flow Rate ft.^{3}/min.
5	1.6	0.32
8	2.6	0.50
10	4.0	0.74
12	5.6	0.91
14	8.5	1.38
18	13.8	2.22
25	23.3	3.69
30	30.0	4.80
40	43.0	7.0
50	56.5	9.2
60	70.5	11.4

the top was met, after falling a few feet, by an upward airstream imparting a swirl to the dust cloud and distributing it evenly throughout the chamber. The suction leg of the injector dipped into the cylindrical glass vessel floating in water. This vessel was slowly and constantly raised by a water balance. As the dust came within $\frac{3}{4}$ in. of the foot of the suction tube it was picked up by the swirling air emerging from a "six" cut brass spiral with a "twelve" cut spiral slipped over it and carried into the injector.

Two holes were cut in the top of the chamber, one circular, to accomodate the mouth of the injector, the other rectangular. The rectangular opening was fitted with a movable cover with three holes. Two of the holes carried the leads to the thermal precipitator head which was held in position by a wire through the third hole. A source of illumination was fitted inside the dust chamber to aid visual estimation of the dust concentration. Cone shaped sampling orifices of 1 in., 2 ins., 3 ins., 4 ins., 5 ins., 6 ins., 7 ins., 8 ins., 9 ins., and 10 ins. were made from 20 S.W.G. brass sheet. These orifices could be fitted inside the dust chamber as shown in Fig. 41. A modified apparatus was employed in this section of the work, Fig.42. This consisted of an airtight cylinder of 16 S.W.G. copper tube, with a knee adaptor to which was attached the air ejector and silencer. At the foot was a

FIGURE 41

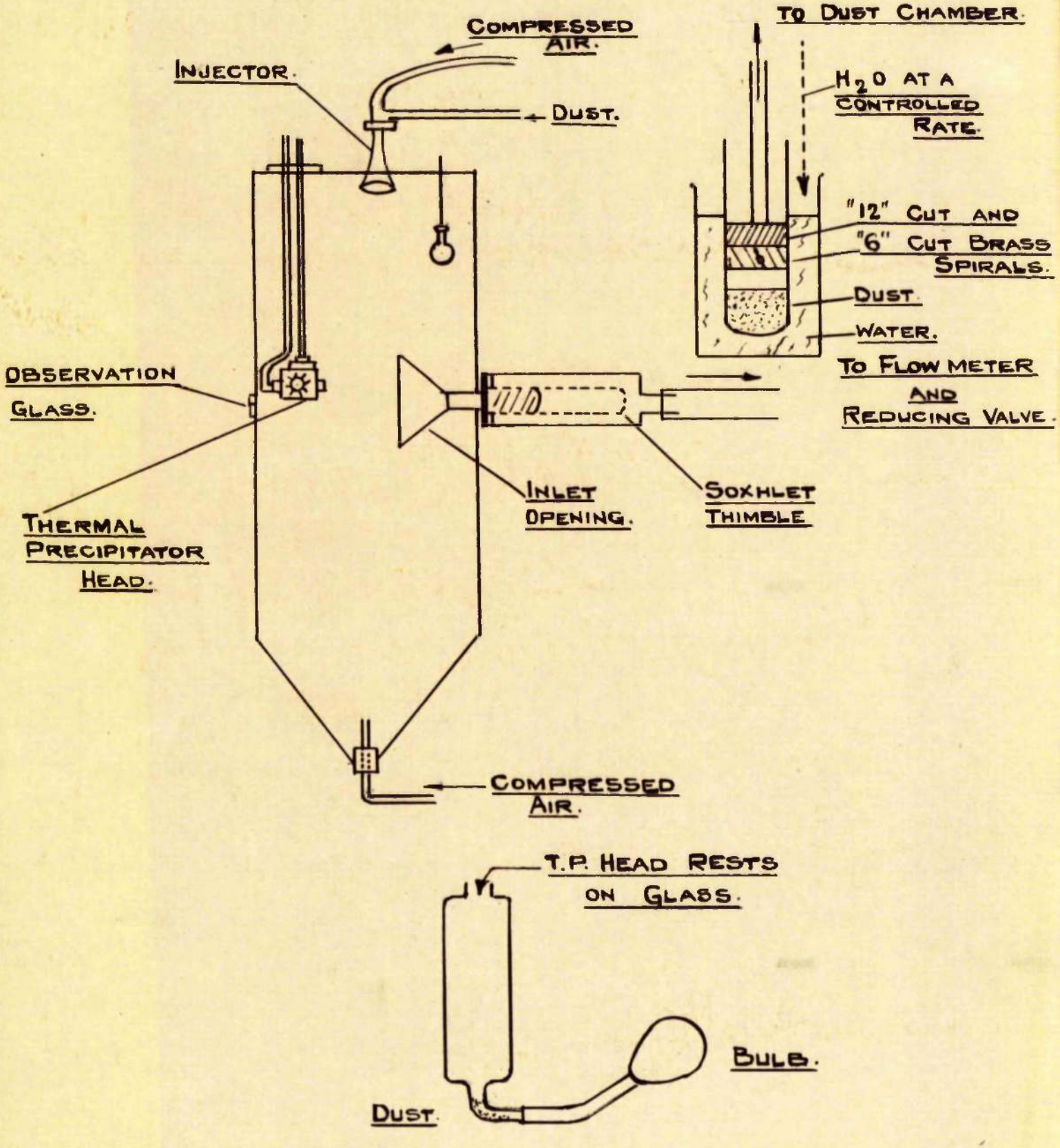
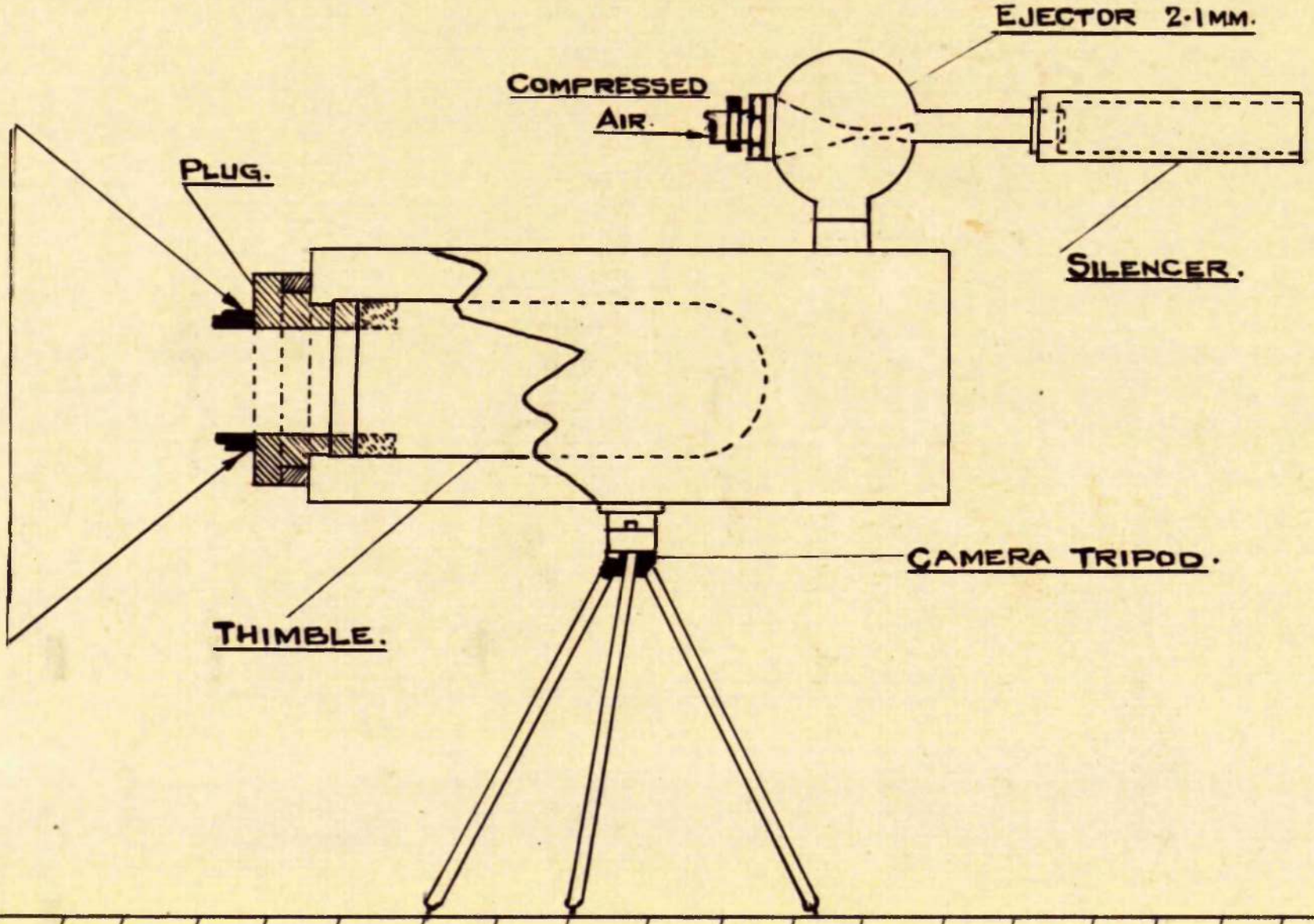

TO DUST CHAMBER.
COMPRESSED AIR.
INJECTOR.
DUST.
H_2O AT A CONTROLLED RATE.
"12" CUT AND
"6" CUT BRASS SPIRALS.
DUST.
WATER.
OBSERVATION GLASS.
TO FLOW METER AND REDUCING VALVE.
THERMAL PRECIPITATOR HEAD.
INLET OPENING.
SOXHLET THIMBLE
COMPRESSED AIR.
T.P. HEAD RESTS ON GLASS.
BULB.
DUST.

FIGURE 42

DUST SAMPLING APPARATUS

(NOT TO SCALE)



swivel pin and brass support plate which enabled the sampler to be raised or lowered keeping its mouth in a horizontal position facing the ventilation stream. The filter, a Soxhlet thimble, slipped over a brass adaptor and was held by a retaining clip. The adaptor, with filter attached, was then screwed into the cylinder. The inlet cone was attached by means of a coupling.

Experimental

The trials were carried out with a constant dust cloud of ca 2,000 particles per cubic centimetre and at a constant sampling rate of 2.5 ft^3/ min. Table 69 shows the variation in dust concentration over 8 hours run.

A Soxhlet thimble was dried at 104° C. to constant weight. It was then attached to the apparatus and sampling commenced.

Sampling was continued for 8 hours, Thermal Precipitator samples being taken at half-hourly intervals. At the end of the 8 hours the thimble was removed and dried to constant weight. This procedure was repeated until 8 hour runs had been made with each size of sampling orifice, projecting 7.5 in. into the dust chamber. In order to prepare a slide of the collected dust suitable for microscopic examination the glass tube shown in Fig. 41 was used. The thermal precipitator head fitted into the top of the tube. To obtain a sample a small amount

Table 62

Time hrs.	Dust Concentration p.p.c.c.
½	2400
1	2150
1½	1800
2	2230
2½	2180
3	1750
3½	1940
4	2310
4½	2120
5	1900
5½	2360
6	2600
6½	1860
7	1670
7½	2050
8	2110

of dust was placed in the narrow limb and blown up into the tube to form a dust cloud which was then sampled.

Results

The weight of dust collected in each case and the average suction over the sampling area is shown in Table 70. A maximum weight was obtained when the 5 ins. diameter opening was used. The histogram of the particle size distribution of the dust cloud and dust collected, Fig. 43, shows the tendency of the heavier particles to shoot on past the sampling orifice at sampling velocities greater than isokinetic, especially with the smaller sizes of orifice.

The failure of the larger diameter orifices i.e. >5 ins. to collect heavier samples appears to be due to the lower suction per unit area. If, however, a higher rate of suction could be maintained a larger weight of dust should be obtained with a 10 ins. diameter orifice giving greater sampling accuracy.

Considering again the factors affecting sampling, Table 71 shows how the 10 ins. diameter orifice best satisfies the conditions for accurate sampling under the working pressure of 60 lb./in.^{2} (sampling rate 11.4 ft.^{3}/min.) for 0.2 micron and 3 micron particles.

Underground trials with the above apparatus gave the results shown in Table 72. It can be seen from this table that 136 hours

Table 70

Dia. of Sampling Orifice (ins.)	Area Over Which suction is spread in^2	Suction mm/in^2	Weight of dust collected gm.
1	0.95	102.1	2.7842
2	3.47	28.0	3.6880
3	7.55	12.84	4.0103
4	10.75	9.02	4.4680
5	19.64	4.94	4.8069
6	28.30	3.93	3.6586
7	38.50	2.52	2.4793
8	47.70	2.03	2.3213
9	63.60	1.53	1.9729
10	78.50	1.24	1.6097

FIGURE 43

SILICA DUST.

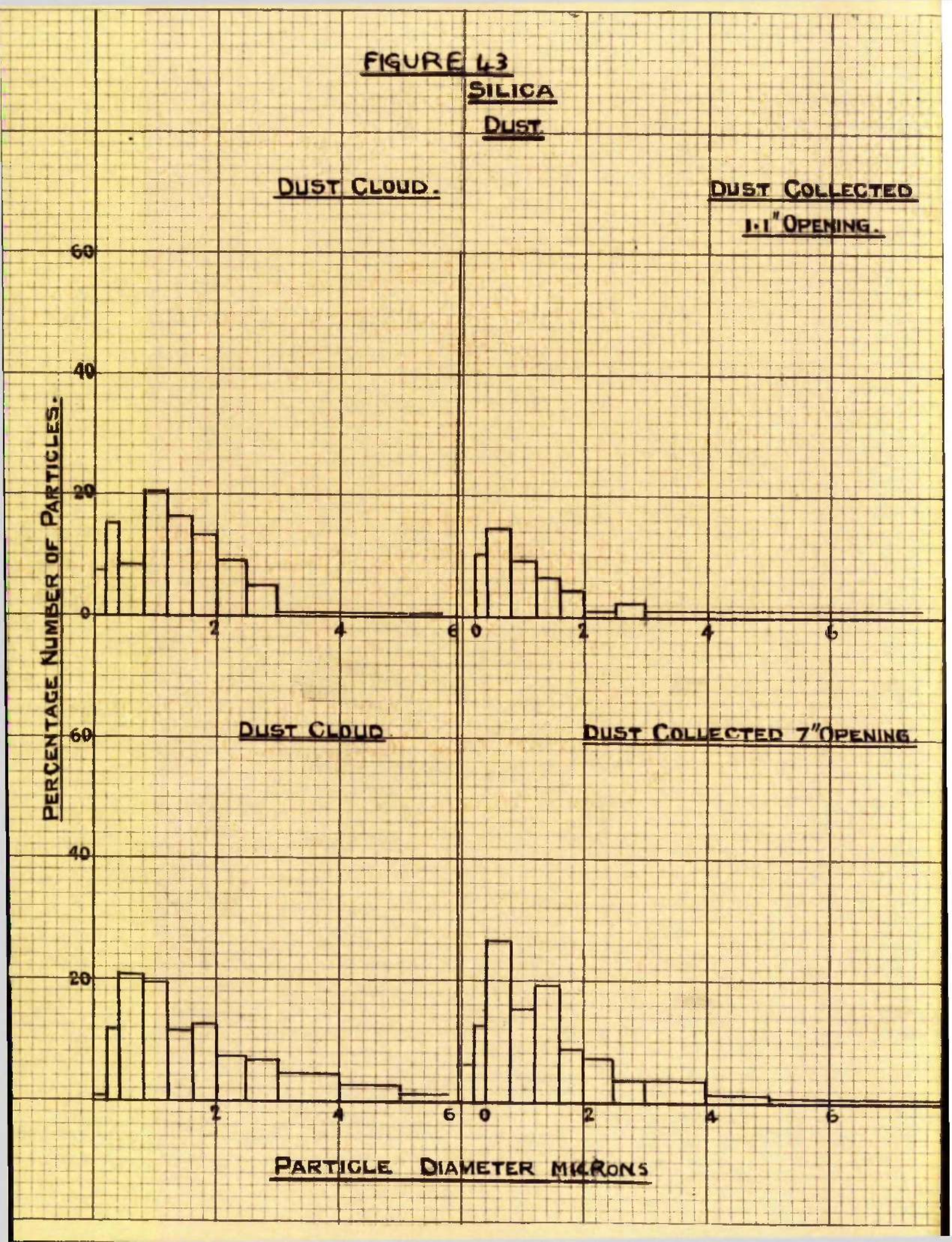


Table 71

Diameter of Sampling Orifice	Particle Parameter P		Velocity Ratio Va/Vs
ins.	0.2 microns	3.0 microns	
1	0.0254	5.7	0.132
5	0.0056	1.26	2.73
10	0.00056	0.126	3.50

Table 72

Sample	Weight gm.	Duration of Run hrs.	Mean Dust Concentration (1-5microns) p.p.c.c.	Average Particle Size microns	Rate of collection mgm./hr.
K.1	2.0	120	258	3.4	16.7
K.2	1.2	120	164	2.35	10.0
K.3	2.5	120	381	2.97	20.8
K.4	2.5	90	272	4.05	27.8
C.1	13.2	145	1028	4.29	91.0
C.2	2.2	48	286	3.20	45.8
C.3	5.5	48	244	3.64	115
C.4	11.7	48	568	3.63	244
C.5	1.4	144	123	3.62	9.7

of continuous sampling would be required in order to collect 5gm. of dust, average particle size 1 - 5 microns from a dust cloud of 400 - 500 particles per cubic centimetre.

The weight of dust retained in the pores of the thimbles did not exceed 100mgm. in each irrespective of the duration of the trials.

Comparison With Hexhlet Dust Sampler

Since the design and manufacture of this portable sampler the Hexhlet dust sampler has been produced commercially by Messrs. Casella (111) from a design by Wright (142). It was thought desirable to compare its performance with that of the dust sampler, previously described, (H - J Sampler).

The Hexhlet sampler is essentially the same as this sampler but it incorporates a horizontal elutriator with the aim of collecting only the respirable fraction of the airborne dust in the thimble. This elutriator is designed to collect 50 per cent of particles of unit density 5 microns in diameter when the volumetric flow rate is 100 l./min.

Apparatus

The dust chamber described in page 64 was used. A hole was cut in the chamber and adaptor plates made. These enabled the mouth of both samplers to be inserted 7½ ins. inside the chamber.

For this comparison both coal and silica dust were used. These dusts were prepared by grinding in the mechanical agate mortar for 5 hours. Since the sampling rate was constant at

70 l./min. as before, the elutriator should theoretically collect 80 per cent of particles of unit density 5 microns in diameter.

Procedure

The apparatus was fitted up, the dust cloud blown in and sampling commenced. Sampling was continued for 8 hours, during which period Thermal Precipitator samples were taken hourly. After 8 hours the thimble was removed, dried and the recoverable dust weighed. Both coal and silica dust were sampled in the same way. The Thermal Precipitator slides were examined and the dust cloud concentrations evaluated. Particle size analyses were carried out on the slides prepared from the collected dust. The sample taken at the fourth hour was used to measure the size distribution of the dust cloud.

Results

The weights of dust obtained over 8 hours with a dust concentration of ca 2200 particles per cubic centimetre are shown in Table 73 below.

Table 73

Weight of Dust Collected gm.

	Silica Dust	Coal Dust
N-J Sampler	2.4689	3.3756
Hexhlet		
Thimble	0.2652	1.3175
Elutriator	2.2313	1.3965
Total	2.4965	2.7140

The particle size distributions are shown in histogram form in Figs. 44 and 45 for coal and silica dusts.

Conclusions

Table 73 shows that the weight of dust in the thimble of the H - J collector is much larger than that in the Hexhlet thimble. Including the weight of dust in the elutriator, however, the total weights collected show very little difference.

Comparison of the histograms shows that both samplers give a good average sample of the airborne dust. Size distributions of the dust collected from both Hexhlet thimble and elutriator, Figs. 45 and 46, show very little difference. The horizontal elutriator on the Hexhlet does not appear to be very effective as in each case particles >5 microns appear in the thimble fraction.

FIGURE 44.

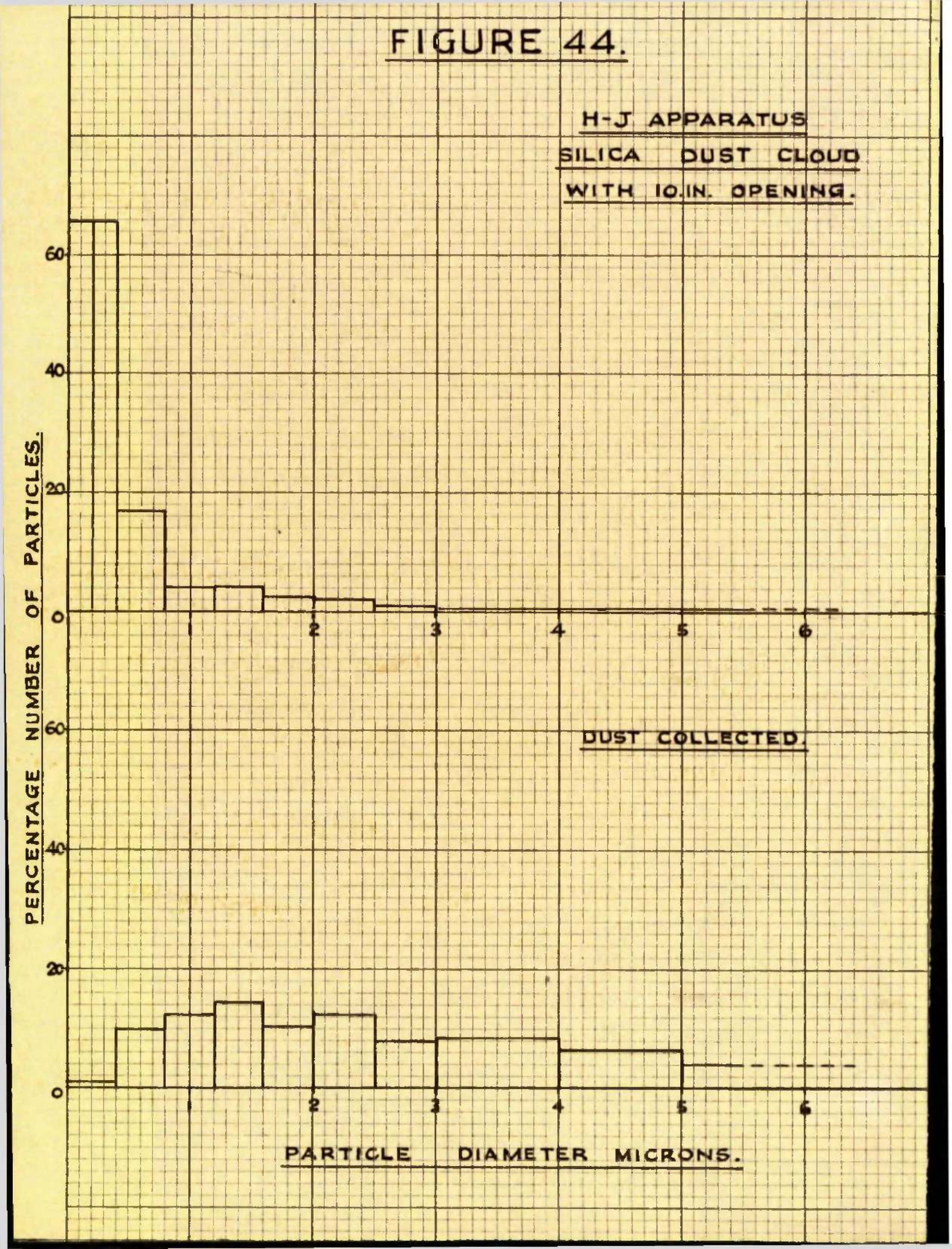

H-J APPARATUS
SILICA DUST CLOUD
WITH 10 IN. OPENING.
PERCENTAGE NUMBER OF PARTICLES.
60
40
20
0
1
2
3
4
5
6
DUST COLLECTED.
60
40
20
0
1
2
3
4
5
6
PARTICLE DIAMETER MICRONS.

FIGURE 45

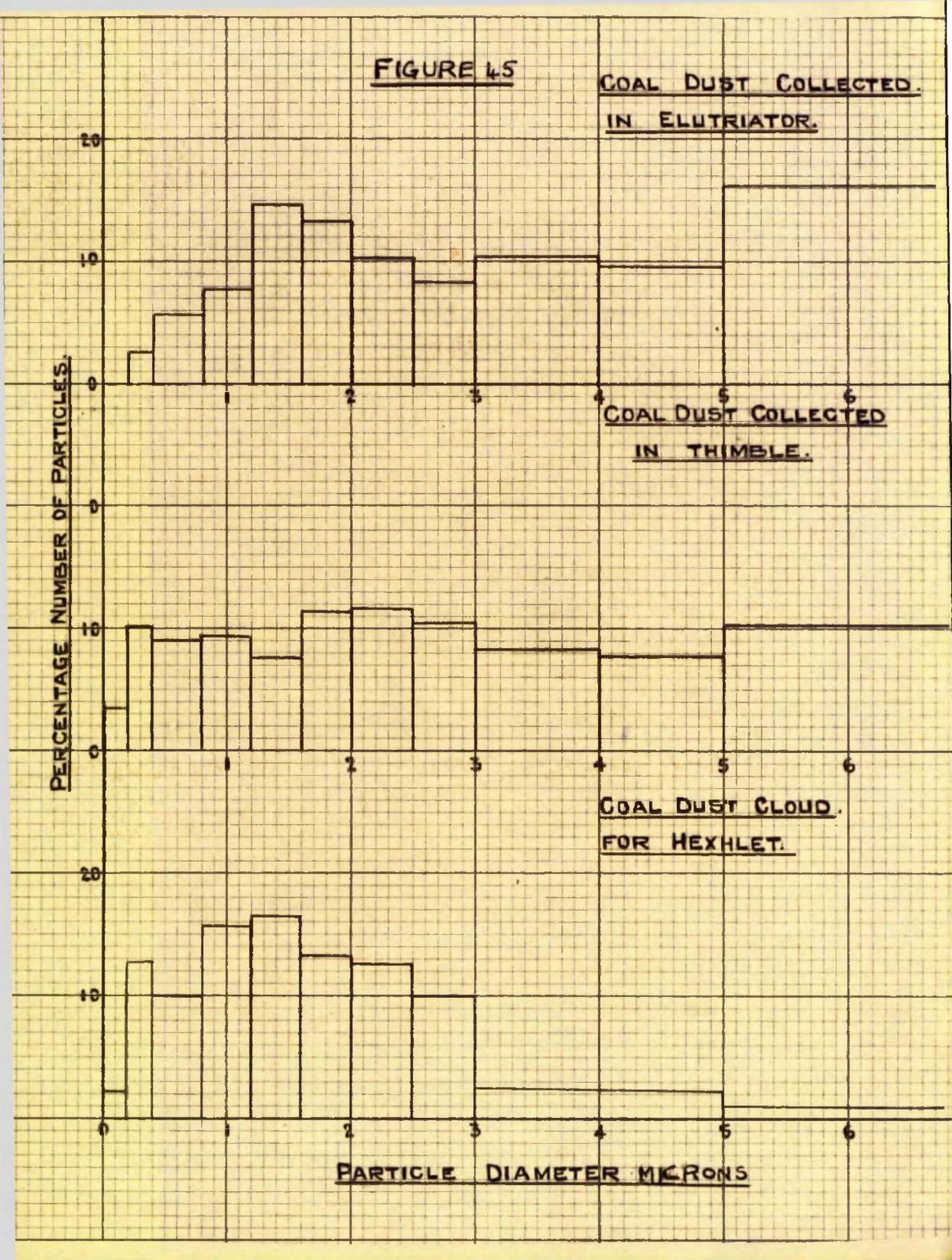
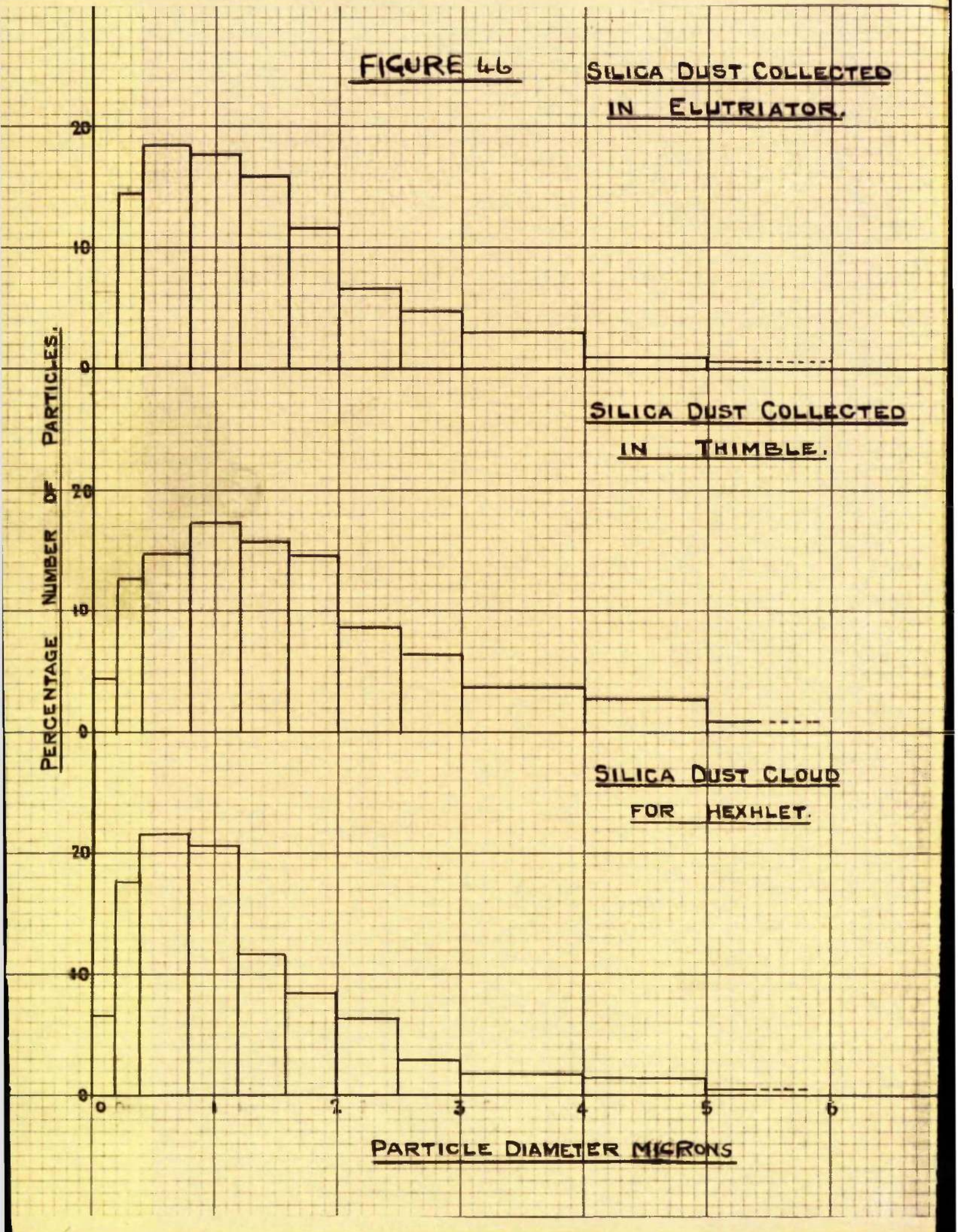

COAL DUST COLLECTED IN ELUTRIATOR.
COAL DUST COLLECTED IN THIMBLE.
COAL DUST CLOUD FOR HEXHLET.
PERCENTAGE NUMBER OF PARTICLES.
20
10
0
1
2
3
4
5
6
PARTICLE DIAMETER MICRONS

FIGURE 46


SILICA DUST COLLECTED IN ELUTRIATOR.
SILICA DUST COLLECTED IN THIMBLE.
SILICA DUST CLOUD FOR HEXHLET.
PERCENTAGE NUMBER OF PARTICLES.
20
10
0
20
10
0
20
10
0
0
1
2
3
4
5
6
PARTICLE DIAMETER MICRONS

Conclusions

The swirl type of spray nozzle was thoroughly investigated and a method developed for sampling it. It was found to give a spray with reproducible size distribution and average droplet size.

It was possible to connect the spray variables by an empirical formula by which the average droplet size may be predicted at any pressure provided two relevant points were determined experimentally. A relationship was also obtained between the energy applied to the spray and the energy actually used in the atomisation process.

In general, atomisation was found to increase with increase in spray pressure and cone angle and decrease with increase in orifice diameter and with distance from the nozzle.

An efficiency of atomisation was determined and the values obtained were much lower than expected, indicating that a high proportion of the energy imparted to the spray was not utilised in the atomisation process.

The atomisation achieved using solutions of low surface tension was similar to that obtained using water. Only at low pressures, 30 lb./in.^{2}, was any improvement gained. Due to the nature of the fluids employed, another method of droplet sampling was used, an impressions method, and gave comparable results to the method employed in sampling pure

water sprays, immersion liquid.

The energy required to effect equivalent atomisation with these liquids of low surface tension appeared to be low but a corresponding increase in atomisation at the same spray pressure was not achieved. This would indicate that the value of liquid surface tension employed in the calculation, equilibrium value, was at the instant of droplet formation not the true value.

In so far as change of surface-active agent concentration affects the surface tension of the solution, change in concentration was found to affect atomisation only at low pressure. At higher pressures concentration of surface-active agent would only affect atomisation through viscosity or density increases.

Fine airborne dust clouds were affected by water sprays the change in concentration obtained being dependent on the spray variables. The amount of dust removed was in each case increased when

(a) the duration of spraying was increased

(b) the degree of atomisation was reduced

(c) the relative velocity of the droplets was increased

It appears that an optimum value of droplet size >100 microns exists when suppressing dust 99 per cent < 5 microns.

Droplet size appears also to be the main controlling factor in the suppression process, the effect of relative velocity being much less than expected.

The degree of suppression obtained was slightly better in the case of coal and silica dusts. Microscopic examination showed that the coal and silica dust particles were very irregular while the fly ash particles were almost spherical. It would appear therefore that it is easier to "knockdown" irregularly shaped particles.

It has also been shown that values of the "effectiveness" of removal obtained agree well with those deduced from the theoretical studies of other workers.

Most of the solutions of low surface tension had virtually the same effect as water on the dust clouds. The exceptions were calcium chloride solution, which proved much less effective, and cycloHexane which was slightly better than water with each dust.

At low pressure, 30 lb./in.^{2}, more dust was removed than at 60 lb./in.^{2} indicating perhaps the advantage of using large droplets.

cycloHexane was a much better dispersive agent than water with the dusts employed but the improvement gained in using this liquid was in no measure due to the solubility of the

dusts in it.

The size distribution of the dust clouds altered very slowly with time after the first 90 minutes, only the larger particles being affected to any great extent. During this initial period a number of aggregates formed and settled out rapidly, the dust cloud then becoming fairly stable.
In the next few hours some aggregation of the smaller particles occurred and the clouds settled under gravity. Decrease in the number of particles in suspension in the chamber was therefore due to two factors :

(a) aggregation of the small particles to form large aggregates

(b) sedimentation of the large aggregates from suspension.

Water sprays resulted in increased removal of dust, especially the larger particles, >1 micron. More of the larger particles were removed the higher the spray pressure. It would again appear that an optimum droplet size >96 microns existed for the clouds sprayed.

The effect of spraying was to remove most of the larger dust, >2 microns, which although leaving most of the harmful dust in suspension, reduced the total contamination of the atmosphere, thus lessening the health hazard.

No advantage over water was gained by using solutions of

low surface tension, the most dangerous fraction of the dust remaining in suspension. This was also true at 30 lb./in.^{2} where surface tension was found to have a greater effect on droplet size.

cycloHexane appeared to remove some of the dangerous size fraction but it would be impracticable to use this liquid underground as it might be injurious to health and would give an inflammable mixture.

An airborne dust sampler has been developed which is capable of collecting a representative sample of the dust in suspension. The weight of dust collected in a reasonable time is sufficient for gravimetric chemical analysis to be carried out.

It has been shown to compare favourably with another bulk sampler now being produced commercially.

General Discussion and Suggestions for Future Work

The apparatus and technique employed in this work has enabled a great deal of information to be obtained on the characteristics of the swirl type of spray nozzle and the suppression of airborne coal dust, silica dust and fly ash of small particle size. It would appear from this work and from the literature read that more information is required on the fundamentals of the suppression process.

It should be borne in mind when considering the suppression results that the spray will be more efficient in the dust chamber employed than under ordinary working conditions. The reason for this is the confined space and turbulence in the chamber, which increases the likelihood of contact between droplet and particle. After the initial spraying period a relatively high humidity exists in the chamber which also contributes to improved suppression.

Reducing the problem of suppression, complicated by the multiplicity of particle and droplet sizes used in this work, to the simple action of one droplet striking and carrying down one particle we have to consider an ideal system. Future work should therefore be done using one droplet and measuring its effect. It would be more practicable to study the effect of a spray of uniform droplet size on dust clouds

of constant particle size. A spray of almost uniform droplet size could be obtained by using a battery of hypodermic needles (143). Work of this nature should enable the most effective droplet size to be accurately determined.

Very small droplets in the form of a mist may increase the permanence of dust clouds. Below a critical size spraying may therefore hinder removal and tend to maintain high dust concentrations.

The results have shown that airborne dust clouds are affected by aqueous sprays but that no advantage over water was to be gained by using liquids or solutions of low surface tension.

When liquids are forced through a nozzle at high pressure they possess a dynamic value of surface tension, which for many of them differs greatly from their equilibrium surface tension value. Addison and Elliot (106) showed that the dynamic surface tension value of certain alcohols, at the moment of issue from a nozzle was about twice the normal equilibrium value. This may have been the case with the liquids used in the experiments and if so would account for the similarity of their behaviour to pure water. This would also explain why the average droplet size calculated from energy considerations, for the liquids of low equilibrium surface tension was found

to be higher than expected.

Cyclohexane unlike the other liquids, showed some ability to allay the dusts more effectively than water. Further investigation failed to give a reasonable explanation of this property but the answer may lie in its dynamic surface tension value at the moment of contact with the dust.

Although the use of cyclohexane in mines would be impracticable it would be of interest to study the behaviour of similar liquids and to correlate their dynamic surface tension values with their suppression efficiency. Work of this nature might supply information of fundamental importance.

The method employed to estimate the dust concentrations and study the changes in size distribution of the clouds was accurate but time consuming. Several quicker methods are available but most, such as the sonic method (144) are as yet too inaccurate for this type of work. Optical methods based on the measurement of scattered light are however very promising (122). Difficulties do occur with this method as the sensitivity changes rapidly with particle size in the important range between 1 and 5 microns. The development of such a method to higher accuracy would prove a boon to workers in this field.

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